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THESIS

THE NPS SPACECRAFT COST MODEL: TAILORING CURRENT COMMERCIAL SPACECRAFT COST MODELS FOR NAVAL POSTGRADUATE SCHOOL SATELLITE PROGRAMS

by

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December 1999

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The successful launch of the Naval Postgraduate School (NPS) Petite Amateur Navy Satellite (PANSAT) led to the development of a follow-on satellite program NPSat. Until now, there did not exist a NPS specific cost modeling procedure to ensure accurate pricing information for program management. From the Preliminary Design Review of NPSat an initial attempt at modeling this program was conducted by the author. This thesis will provide an evaluation of this initial model and address procedures for refining the initial estimate with the purpose of providing a generic NPS Cost Model. This model will tailor current commercial cost model outputs to provide accurate price estimates for NPS specific programs. The commercial cost models used were Science Applications International Corporation's (SAIC) NAFCOM model and Aerospace's Small Satellite Cost Model (SSCM). These models do not take into account a university atmosphere where staffs and facilities are reduced. A method of tailoring the outputs of these programs was conducted and integrated into an Excel based spreadsheet. The resultant product is the Naval Postgraduate School's first Cost Modeling program which allows NPS satellite program management to input results from the SSCM and NAFCOM models and output expected cost data.

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ABSTRACT

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I. INTRODUCTION

A. BACKGROUND

This thesis will address methodologies for performing cost modeling of Naval Postgraduate School (NPS) satellites. A comprehensive analysis was conducted of the cost factors for associated program phases of the NPS Satellite (NPSat) program. A risk assessment of resultant data and a probability examination of the projected results provided insight into the expected likelihood of realizing the compiled results. Procedures and results from the NPSat-1 Preliminary Design phase will be addressed and recommended procedures for refining these results will be discussed to provide NPS with an effective cost modeling tool for any on-site designed and fabricated satellite. The resulting tool is a Microsoft Excel based software tool which will allow for future NPS Cost Analysts or Program Managers to use the outputs of commercial cost modeling software as inputs to this program. Once entered, this data is processed through an algorithm which provides for the unique problem of performing cost analysis in a university environment. This document provides details of the initial cost model, a comparison with Stanford University's facilities and capabilities with the satellite design program at NPS, an explanation of the generic NPS Cost Model program, a refined model, and recommendations for reducing costs to the current NPSat-1 spacecraft design.

The main impetus behind effective cost analysis is to predict the cost of a program within some level of probability and accuracy of actual expenditures. The very nature of cost estimation is guessing the future cost or price of a program. In addition, a risk assessment of input and output data must be conducted to account for analysts unfamiliarity with specific programs, confidence in derived numbers or their sources, and the complexity of specific aspects of the program being modeled. For risk assessment, some method of accounting for confidence factors must be instituted to ensure actual cost data reflects the appropriate risk factor associated with the specific derived figures. (Raymond). Also, the derived cost model results should address the probability of achieving these results to provide program management with a realistic range of values for budgeting the program. (Anderson). Security provisions should be formulated in the event these projected values do not materialize. This contingency procedure allows flexibility to the program manager in assuring the program may continue despite unforeseen delays, cost overruns, etc. It should be noted, although cost estimation has continued to evolve into more of a science, it is also an art. There are many instances when an applicable formula or concrete data does not exist so it remains the judgement of the analyst to arrive at his or her best guess. To the knowledge of the author, there currently does not exist commercial software dedicated to performing cost analysis of university based satellite programs. The main objective of this thesis will be to explain the preliminary analysis of NPSat and outline the NPS Cost Model which will perform a cost analysis for NPS spacecraft. Due to the lack of supporting evidence for university based models, there are instances where sound engineering judgement was relied upon from inputs of industry experts or NPS staff and faculty. The only method to judge the validity of the NPS Cost Model will be when the actual expenditures for the NPSat-1 program are compared with the forecast cost. It is imperative accurate tracking of dollar expenditures, personnel labor, and other costs is performed in order to compare forecast cost versus actual cost.

Tools that we can use to more effectively perform a cost analysis are parametric estimating (usually software programs), Cost Estimating Relationships (CERs), Work Breakdown Structures (WBS), Cost Breakdown Structures (CBS), and direct comparisons with existing satellite programs which closely resemble the program being modeled. Parametric estimating is a technique that uses validated relationships between a project's known technical, programmatic, and cost characteristics and known historical resources consumed during the development, manufacture, and/or modification of an end item. (Parametric Estimating Handbook, Chapt.1, p.1). CER's are defined as mathematical expressions or formulas that are used to estimate the cost of an item or activity as function of one or more relevant independent variables, also known as cost drivers. An example of a CER for the initial cost estimation for a satellite is provided in Equation (I-1). (Wertz and Larson, Space Mission Analysis and Design, Tab. 20-5).

$$\text{Bus Cost (FY 1992\$)} = 185 * (\text{Bus Mass})^{0.77} \qquad \text{Eq. I-1}$$

Parametric models are more complex than CERs because they incorporate many equations, ground rules, assumptions, logic, and variables that describe and define the particular situation being studied and estimated. Parametric models make extensive use of databases by cataloging program technical and cost history. (Parametric Estimating Handbook, Chapt.1, pp. 1-2). These models typically use parametric equations which rely on forecast cost drivers: spacecraft bus mass, power, subsystem performance, sensor accuracies, etc. Commercial software programs routinely apply these parametric techniques inherent in a database to arrive with a more defined modeling approach, such as Aerospace's Small Satellite Cost Model (SSCM). Many industry and Government representatives recognize parametrics as a practical estimating technique that can produce credible cost estimates. In a memorandum to Directors of Defense Agencies, the Director of Defense Procurement for the Office of the Under Secretary of Defense, Mrs. Eleanor Spector states,

> I fully support the use of properly calibrated and validated parametric cost estimating techniques on proposals submitted to DOD, and I encourage your enthusiastic support . For many voluminous bills of materials and grass roots engineering estimates of hours which must be audited and updated throughout the course of a lengthy negotiation. Instead we could rely on parametrics to price early design/development effort, portions of follow-on production buys, or any other effort where verifiable data exists to price parametrically. (Parametric Estimating Handbook, pp. vii).

WBS are itemized task lists with associated costs for each task, i.e., the labor and material cost associated with the fabrication of a honeycomb aluminum panel. The WBS approach requires lengthy and often extremely tedious tracking of specific task cost dependent on the level in which the WBS structure has been broken down. For early program cost estimates, the WBS is usually not the method of choice. The CBS or "grass roots" method allows for a detailed method of determining projected cost of circuit boards, components, subsystems, and systems hardware. This approach can be used in the early stages at the component level from vendor quotes on actual hardware prices. Direct cost comparisons with existing programs have the advantage of observing a spacecraft's planned cost with the actual cost and contingencies experienced during the life of the program. The disadvantages associated with this technique are the requirement to intricately know the capabilities of the observed programs personnel and facilities and the cost data is usually sensitive. In the "Journal of Reducing Space Mission Cost", Dr James R. Wertz points out,

> There are many reasons for this sensitivity including the proprietary nature of much of the data and the fact that for space systems, cost depends far more on what the vendor is required to do than what is actually being built. One of the best ways to make cost data known, without jeopardizing proprietary data, is to make cost models public. Some models are created at private expense and, therefore, should be allowed to remain proprietary so that the developer can sell the information to run a profitable business. However, many cost models are created at public expense, either directly by government agencies or by federal research centers or private contractors under government contracts. In these cases, the cost models themselves (but not the proprietary data on which they were based) should be made publicly available as a fundamental knowledge resource for the community as a whole. (Wertz, pp. 5-6).

No two programs are exactly alike, weather may delay a vehicle launch, testing facilities scheduling may be delayed, engineers may retire, etc. So the direct comparison technique presents many difficulties in accurately depicting expected costs for a future satellite. (Preliminary Design Report, p.8).

With the successful launch of NPS's Petite Amateur Navy Satellite (PANSAT), there has been continued interest in the design and fabrication of future NPS satellites. For these follow-on satellites, the obvious choice for a cost comparison for future programs would be this PANSAT program. However, it is imperative one must consider the complexity of the future spacecraft and the availability of accurate historical cost data. Unfortunately, PANSAT will not be a good choice for a comparison due to the lack of historical cost data. Proposed future NPS satellites will be more complex in mission, attitude control, data transfer and processing, and will eventually incorporate propulsion.

The author attempted to gather various university-based projects for this report to use as valid cost comparisons. However, the proprietary dilemma Dr. Wertz discusses did prove to be a formidable obstacle. The following satellite programs were referenced for possible comparisons with the NPSat program:

- The Fast Auroral Snapshot Explorer (FAST) of NASA's Small Explorer (SMEX) program. This program provides frequent flight opportunities for highly focused and relatively inexpensive space missions. SMEX spacecraft are 180 to 250 kg with orbit-average power consumption of 50 to 200 watts. Each mission is expected to cost approximately $35 million for design, development, and operations through the first 30 days in orbit. SMEX programs are managed by NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD. Mission Set One consists of the FAST, Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX), and the Submillimeter Wave Astronomy Satellite (SWAS). The first Small Explorer missions selection announced April 4, 1989, were to study important questions in space physics, astrophysics, and upper atmosphere science. FAST would investigate the processes operating within the Auroral region and would be launched in mid-1996. (SMEX Homepage).
- The University of Colorado's (UC) successful Student Nitric Oxide Explorer (SNOE) program is an ideal spacecraft from which to base a cost comparison for NPSat. The SNOE program is part of the Student Explorer Demonstration Initiative (STEDI). This three year program aims to demonstrate that high-quality space science and technology missions can be carried out with small, low-cost, free-flying satellites on a time scale of two years from go-ahead launch. The STEDI announcement of opportunity was released on May 12, 1994 and out of 66 proposals three satellite programs were chosen, SNOE, Boston University's Tomographic Experiment using Radiative Recombinative Ionospheric EUC and Radio Sources (TERRIERS), and the University of New Hampshire's Cooperative Astrophysics and Technology Satellite (CATSAT).

(STEDI). Dr. Charles Barth, SNOE's Principal Investigator was very helpful in providing spacecraft details and some programmatic data. The author was unable to visit UC's Laboratory of Atmospherics and Space Physics (LASP) due to their high tempo of operations. Phase II, Design and Development expenditures were provided and some labor figures, but there was not enough detail in labor dollars, hours, and personnel to accurately perform a comparison with the NPSat-1 program and Colorado's successful SNOE program. For follow on analysis to this thesis, a meeting with LASP staff members to discuss more specific cost details is recommended. In addition, an analysis of LASP's satellite development facilities and capabilities must be conducted in order to perform an accurate comparison.

- Stanford University in Palo Alto, CA was also contacted as an additional source. Dr. Robert Twiggs, the Director of the Space Systems Design Laboratory (SSDL) was more than helpful in providing useful information and demonstrated the capabilities of their facility on a personal tour in October, 1999. Dr. Twiggs contributed estimates on expenditures, labor hours, and personnel involved in completed and future SSDL satellite missions via Cost Estimation templates provided by the author. Although Stanford's satellite programs are dedicated to smaller microsatellites (usually less than 50 kg) than the proposed NPSat, their method of design and development is impressive and should be addressed. More details on Stanford's satellite programs are discussed later in this document.

Of these three programs, only Stanford's philosophy will be addressed. SNOE and FAST data is still outstanding and was unavailable upon the time of writing this thesis. Their information should be included in any follow-on cost NPS cost analysis. In addition, it was recently learned from the NPSat Chief Scientist, Professor Chris Olsen, that the University of Colorado may become an active participant in the NPSat program.

The interest in a follow-on to PANSAT led to the conceptual design of the NPSat-1 satellite from Space Systems Engineering students during the summer quarter of 1999 in the AA 4871 Spacecraft Design II class. Under the direction of Professor Barry Leonard, the class produced a preliminary design of a three axis stabilized spacecraft with a mission objective of delivering this satellite to Low Earth Orbit (LEO) and imaging the Earth's Aurora with a mission life of one year. During this design effort, the author of this thesis was the Design Team Lead and Cost Analyst.

As with any spacecraft design program, an accurate means of performing a cost analysis was sought with the intention of providing NPSat Program Management with expected expenses over the life of the program. In today's world of "faster, cheaper, better" satellites (Wertz, p. 7), it is imperative an accurate analysis of cost and risk is conducted due to this new philosophy with reduced heritage. Larger, more expensive programs routinely had a long line of in-house programs from which comparisons could be made to provide a baseline for future missions. This alleviated the necessity for meticulous cost modeling and provided some security in budgeting future missions. With the shift to smaller satellites at reduced costs, this is no longer the case. In the 1960s, satellites (Alpha, Pioneer, Explorer) were small inexpensive and built to answer basic questions about Earth and near space. They were simple by nature, primarily due to limited experience in satellite design and early launch vehicle capabilities. As knowledge about spacecraft and launch vehicles grew, the Government and its satellite contractors, gravitated to large, sophisticated, and expensive platforms to meet increasingly demanding mission requirements. During the 1970s and 1980s, satellites carried more powerful and often multiple payloads. Development costs were high as engineers and scientists advanced testing techniques, hardware design, and software development to achieve high degrees of success and longer-life operations. Major spacecraft grew to more than one billion dollars and required decade-long development schedules. In the 1990s, Government spending in the area of space science and technology experienced dramatically increased fiscal scrutiny in the face of declining budgets. The constrained environment led to changes in the way space systems were conceptualized, financed, developed, launched, and operated. In parallel with the realization that funding for the large, highly capable missions of the past would no longer be available, the terrestrial microelectronics and software revolution reached space systems. Program Managers were forced to look more aggressively at advanced technology to pack more capability into smaller systems and to fit onto smaller, less expensive launch vehicles. (Bearden, pp. 1-2). Suddenly, the satellite industry was faced with the dilemma of formulating accurate models without the benefit of heritage missions. This has led to the increased use of parametric data and small satellite oriented cost models.

B. SCIENCE APPLICATIONS INTERNATIONAL CORPORATION'S NAFCOM COST MODELING PROGRAM

The NASA/Air Force Cost Model (NAFCOM) is a parametric estimating tool for space hardware. It is based on historical space projects and is intended to be used in the preliminary design phases of satellite development. This model can be used at the subsystem or component levels of a WBS for up to five different spacecraft systems. The NASA Cost Model (NASCOM) database was developed for the Engineering Cost Office of NASA's Marshall Space Flight Center in 1989. The initial model reflected this name until 1997 when Air Force data was incorporated and the name changed to NAFCOM. Data was derived from source documentation found in NASA's Resource Data Storage and Retrieval (REDSTAR) database. The NAFCOM model contains 100 space projects including 78 unmanned spacecraft, 8 manned spacecraft, 4 engines, and 10 launch vehicles. (NAFCOM Training Course). The following are some additional capabilities of the NAFCOM model:

- Four methods for building the WBS: Specific analogy with existing satellite in the database, database averages, user defined equations, and roll-ups which automatically sum all cost from lower subsystem elements.
- Analogous Estimating for Hardware and System Integration: Analyst may search the database for specific sub-system elements and filter data to create

the most analogous data and cost estimating relationship for hardware and software integration.

- Technical and Programmatic Data: Supplied to provide a better understanding of the background of data, including inheritance and budgetary and scheduling anomalies to assist the user in understanding data points, selecting appropriate analogies, and performing judgements for cost adjusting factors.
- Learning Curves: Option available to provide learning curves for production cost.
- Contingency, Program Support, and Fee: The user may define contingency, program support, and fee percentages to be applied to the estimate. Provides recommended percentages for typical spacecraft programs. (NAFCOM Training).

C. AEROSPACE CORPORATION'S SMALL SATELLITE COST MODEL (SSCM)

The SSCM is a parametric cost model which runs on any Microsoft Excel-supported platform. The latest version, SSCM98, estimates the development and production costs of a small satellite bus for Earth-orbiting or near-planetary spacecraft. The development of this model was motivated by the observation that traditional cost models, based on larger civil and military systems, often times tended to drastically overpredict the development cost of modern, smaller satellites. SSCM98 is the end-result of over ten years of study at Aerospace Corporation. The development of the SSCM has benefited from the efforts of many hours of data collection, normalization, and analysis, and remains one of the most relevant and credible cost models today for performing estimates of small spacecraft. The estimation methodology incorporated is suited to the early, conceptual development phase of a spacecraft program, during which time the design is likely to be less mature, and when cost and performance trades can be easily performed. It consists of a collection of CER's which estimate the costs associated with production of a spacecraft system with the following subsystems:

- Attitude determination and control (ADCS)

- Propulsion
- Electrical Power
- TT&C / C&DH
- Structures & mechanisms
- Thermal control

CERs were also developed for Spacecraft Integration, Assembly and Test, Program Level costs (Program Management and Systems Engineering), and Launch and Orbital Operations Support. The first version of the model relied on an initial database of ten small missions from the late 1980s and early 1990s. Although this initial release focused on Air Force and Department of Defense (DOD) programs, the data gathering strategy has been applied to the (proprietary) acquisition of technical and cost information of over sixty post-1990 earth-orbiting and planetary missions, spanning Air Force, DOD, NASA, civil, and foreign programs. The database used for comparison includes such diverse missions as STEP, FAST, Alexis, MSTI-1, Seastar, APEX, Lewis, NEAR, ACE, Clementine, Mars Pathfinder, DS-1, and Lunar Prospector. Updated versions are produced when a significant number of new satellite cost data are incorporated into the database. There are currently two versions, SSCM98 Pro and SSCM98 Intro. The Intro version was used for the cost analysis performed in this paper and has the following features:

- Runs in Microsoft Excel 95.
- System-level cost estimation.
- Estimate can be generated with as few as one CER and as many as eight (allows for preliminary estimate to made with minimum of available data).
- Estimate is weight-average of applicable CERs.
- Earth-orbiting spacecraft estimating capability only.
- Straightforward interface with spreadsheet based design tools.
- Easy-to-use graphical interface. (Aerospace Corporation).

D. COST BREAKDOWN STRUCTURE (CBS)

A Cost Breakdown Structure provides a method of a "bottom-up" approach for price forecasting. In this method, we identify and specify a lower level of elements making up the system. We then estimate the cost of materials and labor to develop and produce each element. Because this method is time consuming and because detailed design data is usually not available, this method is least appropriate for advanced system studies. An example of a typical CBS for a spacecraft program is provided in Figure 1.

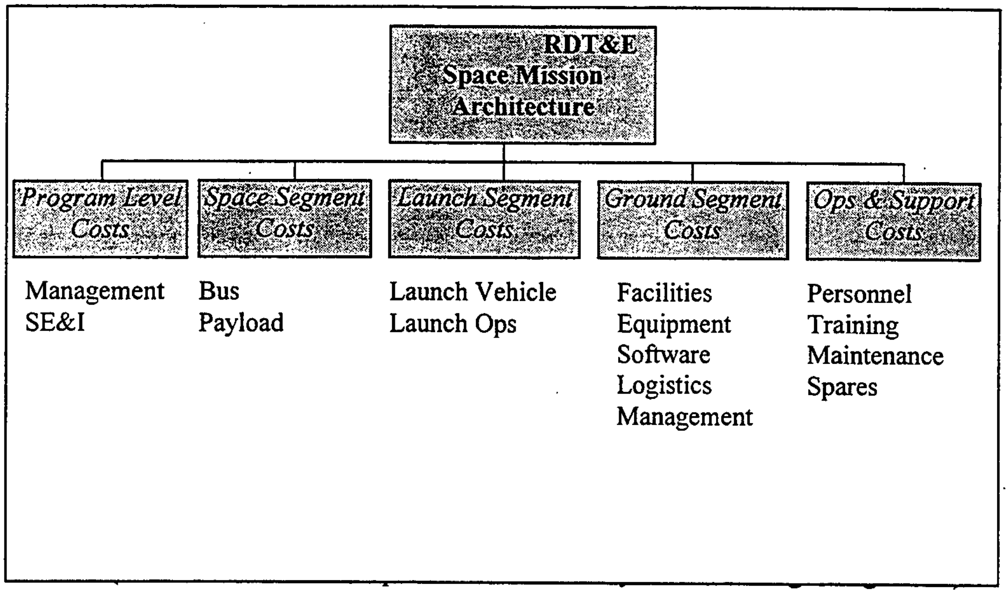

Figure 1. Typical Cost Breakdown for Space Mission.
(Wertz and Larson, Spacecraft Mission Analysis and Design, Fig. 20-2).

A detailed CBS for the NPSat program is provided in Appendix A.

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II. PRELIMINARY COST MODEL OF THE NPSAT-1 PROGRAM

A. NPSAT-1 OVERVIEW

Prior to discussing the specifics of the NPSat-1 cost analysis, a brief summary of the evolution of NPSat and the factors in it's design will be addressed.

In June 1999, NPS Space Systems Operations students presented the conceptual design for the proposed Auroral X-Ray Infrared Imaging Satellite (AXIIS). The follow-on to the PANSAT program, this satellite would also be built by NPS faculty, staff, and students. With an expected on-orbit 1-year lifetime, this 3-axis stabilized satellite would provide imaging data on the earth's Aurora in the northern and southern hemispheres. The proposed configuration of AXIIS and mission requirements included:

- A one-meter cubed structure with a mass of approximately 100 kilograms (kg).
- Near Sun-synchronous polar orbit.
- Mission altitude requirement of 500-1000 kilometers (km).
- Attitude Determination and Control System (ADCS) and Guidance Control and Navigation (GNC) with a pitch momentum wheel, three magnetic torque rods along the spacecraft primary axes, a gravity gradient boom, Earth and star sensors, a magnetometer, and a Global Positioning System (GPS) receiver and antennas.
- A Telemetry, Tracking, and Control (TT&C) and Command Data Handling (CD&H) package requiring twenty megabits per second (20 Mbps) downlink capability.
- Payloads consisting of a Long Wave Infrared (LWIR) Imager, X-Ray Imager, Visible (VIS) Imager, Electron Spectrometer, and Dosimeter.
- Body mounted Silicon (Si) Solar cells on each of the cubic structure's faces. Deployable/Fixed arrays. Six Solar arrays deploy to 30 degrees relative to the spacecraft's longitudinal axis and then lock.

- Attitude knowledge of 0.1 degree and accuracy of 1.0 degree.

Following the AXIIS Concept Exploration (CE) brief in June, Space System Engineering students in the AA 4871 Spacecraft Design II class were tasked with evaluating the AXIIS design and producing a refined design for the Space Systems Academic Group (SSAG) at NPS, the National Reconnaissance Office (NRO), the Naval Research Laboratory (NRL), and spacecraft industry personnel.

In mid September 1999, the X-Ray Imager was deleted from the payload package of AXIIS and the program was renamed the Naval Postgraduate School Satellite or NPSat. NPSat-1 would be the first in a series of proposed modular bus satellites designed, fabricated, and tested at NPS. Designing for a variety of scenarios in launch vehicle environments, the vehicle targeted, in concurrence with the AXIIS report, was the Pegasus.

The ADCS and TT&C packages remained basically unchanged with the exception of the removal of the gravity gradient boom and minor modifications in the performance of these subsystems. The Electrical Power System (EPS), Structure, Thermal, and Mechanisms subsystems did change dramatically. For more details on the NPSat-1 design refer to the NPSat-1 Preliminary Design Report. The NPSat-1 structure is provided in Figure 2.

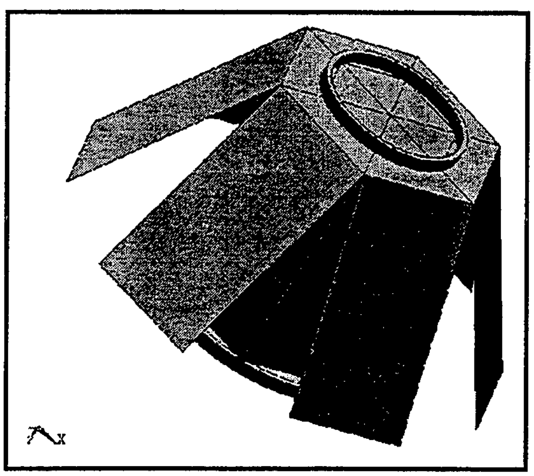


Figure 2. NPSat-1 Deployed Solar Array Configuration.
(NPSat-1 Preliminary Design Report).

B. PROGRAM LENGTH

The originally scheduled launch date for the AXIIS was October 2003. This date primarily reflected the timeline of the LWIR Imager. In addition, no schedule risk management was conducted to control overruns. In an effort to more closely reflect our planned schedule realistically, we addressed the risks involved in different portions of the program and how these risk factors would translate into specific program element durations. (Preliminary Design Report). The method used in doing this was via the Monte Carlo technique discussed by Mr. Fred Raymond from the Naval Research Laboratory in the September 1999 edition of Acquisition Defense Review Quarterly (Raymond). Risk factors associated with the program schedule were applied and the associated multipliers (Appendix B) were used to determine a realistic estimate. The following risk attributes, per Mr. Raymond's article were used:

- Low-risk: Existing proven designs are used extensively; requirements are well defined and readily achieved; development effort is minimal; and an innovative approach materially simplifies design implementation. Extensive use is made of proven hardware of software produced by previous suppliers; exotic processes and tooling are not required for production; materials and parts are readily available; and an innovative approach materially simplifies production.
- Very High Risk: Extensive use is made of new and unproven designs; requirements are poorly defined and unlikely to be achieved; development effort is extensive; and an "innovative" approach materially complicates the design.
- Moderate and High Risk: A grade of "moderate" or "high" is based on the evaluators judgement, considering the risk extremes as defined for "low-risk" and very high risk." Attributes will range from modification of existing design of catalog design to new designs and high technology.

It should be noted, for the preliminary cost estimates and refined cost estimates within this text, "confidence factors" vice risk factors were used for the Monte Carlo applications. A high confidence factor equates to a low risk factor. This convention was based solely on the judgement of the author and does not effect the eventual outcome of the results. In addition to schedule risk management, the Monte Carlo technique was used throughout the cost estimation process to account for the authors confidence in initial estimates.

The Phase I program length was dictated by the start of the program through the Preliminary Design Review (PDR). Since the PDR coincided with the end of the Summer Quarter at NPS, the phase duration of 0.5 months was fairly concrete. The duration of Phase II and Phase III durations came from inputs from Staff Engineers at NPS, veterans of the PANSAT program. They provided a wealth of information on lessons learned and experiences from the PANSAT program. Even with this experience, the NPSat-1 spacecraft would be a more complex satellite and it's program duration would be longer than PANSAT. The Staff Engineers were solicited for their estimates of the program length given a worksheet of basic tasks required to successfully complete the Design and Development (D&D) for the PANSAT program. Fred Raymond's use of the Monte Carlo technique in calculating program durations was referenced and led to the estimated duration for Phase II and Phase III listed in Table 1. (Preliminary Design Report).

Phase	Event	Dates (MM/YY)	Duration
I	Concept Exploration thru Preliminary Design Review	3/99 – 9/99	0.5 Years
II	PDR thru satellite launch	9/99 – 01/04	4.25 Years
III	Satellite launch thru on-orbit operations (End of Life (EOL))	01/04 – 01/05	1.0 Years

Table 1. NPSat-1 Preliminary Program Schedule.
(NPSat-1 Preliminary Design Report).

C. COST MODEL GUIDLINES

In the following paragraphs, the cost modeling approach used by the author during the Preliminary Design Phase will be discussed. This approach is also discussed in the Preliminary Design Report for the NPSat-1 spacecraft. Before we address the approach, some ground rules and assumptions in the NPSat-1 cost analysis must be explained:

- Cost Model results from the NAFCOM and SSCM software programs were scaled down to reflect a university environment. Per Dr. Stephen Book, Aerospace's expert on cost modeling, labor accounted for 85% of the overall program cost from these models. The other 15% of the total was for hardware costs only. Upon Dr. Book's recommendation, 35-55% of the 85% labor cost would provide for a good baseline for a satellite program designed and developed in a university environment. These values were based on Dr. Book's engineering judgement and generic multiplication factors Aerospace uses with university programs based on cost model versus actual expenditure results. (Book).
- Spacecraft spares, testing, and payload/bus integration are included in model results.
- Student labor dedicated to the satellite is "free". Essentially, the use of student labor is transparent to the actual cost for labor. However, through the use of student labor, actual labor hours for staff engineers can be decreased resulting in a decrease in overall labor costs. The "savings" realized with student labor is debatable. An increase in student labor may have a significant impact on the length of the program due to students' lack of expertise when compared to staff engineers. For this reason, for the initial estimate, student labor is not addressed as a method of saving dollars. There was no attempt to increase the projected student labor hours to directly impact the overall program cost for labor.
- Staff and faculty labor costs are direct costs only. There are no indirect

charges included in this cost analysis for NPS staff and faculty personnel. Indirect costs incorporate salary, overhead, and other miscellaneous fees. The Indirect costs would be paid by companies requiring the services of NPS's faculty and/or staff. Since there should be no instance where our personnel are receiving compensation from outside resources, these costs are not included.

- Weighting factors for model complexity or NPS Cost Analyst unfamiliarity with software packages were applied when required. The method for accounting for the confidence in model data or analyst familiarity is the Monte Carlo method of risk assessment. This method uses weighting factors to provide a level of risk management for manipulating data. (Raymond). It should be noted, the factors used provide for a minimum value for all risk codes of 1.0. What this implies is the associated risk assessment will not account for values which may be lower than the expected value. Per Mr. Raymond, the reason for this is the initial estimate should be the "best guess." In instances where there is no best guess, then it may require reducing the Minimum multiplication factor to a value less than 1.0. (Raymond).
- An assumed satellite mass of 150 kilograms (kg) is used for inputs into the SSCM and NAFCOM models. This provided an additional mass margin of approximately 15-25 kg to the existing mass margin calculated by the NPSat-1 Student Structures Subsystem Manager. (Preliminary Design Report, Appendix XI-II).
- For labor hours, a 30% labor margin was used to provide for possible underestimation. This was based solely on judgement by the author for his lack of experience in cost analysis and from discussions with Dr. Book on the historical underestimation of labor figures in cost estimates. This would have no impact on the actual calculation of labor for Phase II due to the use of ratios vice actual estimated hours. These ratios are Staff per Total hours, Faculty per Total hours, and External Engineers per Total hours. Since all of

these personnel divisions incorporate the same 30% margin, the value is actually transparent in the ratio. Phase I and Phase III labor hours use the actual values plus this margin calculated via the Labor Worksheets in the Preliminary Design Report, Appendix III-4.

- A 5% Management Reserve at the program level was instituted to provide a margin within one standard deviation (σ) of the expected average cost for a flight unit. This came to $1,285,473 FY 2003 dollars for out initial cost analysis. As a comparison, the SNOE program had a Management Reserve for their Phase II which equaled approximately $300,000 (Barth, SNOE Cost information). It is not known what percentage this figure is of the SNOE flight unit cost. It appears, due to the similarity between satellite mass and mission for SNOE and NPSat-1, the 5% Management Reserve should more than suffice for contingencies.
- An additional year for on-orbit operations was included due to the high likelihood the spacecraft would last at least two years on orbit vice one year based on reliability calculations in the PDR report. This additional year of operations would ensure the cost analysis provided for an extended program life and would reflect the appropriate costs associated with added on-orbit operations.
- Payload costs are not included in the NAFCOM and SSCM software models results. These values were calculated via the algorithm in Table 2.

Step	Procedure
1	Determine Model result: Program output was total labor and hardware costs for Phase II.
2	Labor with Single Contractor = Model result * 85%.
3	Labor for University Environment = [Step 2] * 30%.
4	Reduction Factor for In-house Testing = [Step 3] * 30%.
5	Labor Subtotal = [Step 3] – [Step 4].
6	Determine miscellaneous labor expenses: Maintenance = [Step 5] * 5%. Overhead = [Step 5] * 10%. Fees = [Step 5] * 5%. General and Administrative (G&A) = [Step 5] * 5%.
7	Staff / Faculty / Outside Contractor Labor = [Step 5] – $\sum$[Step 6].
8	Staff Labor Cost = [Step 7] * Staff labor hour ratio[1]. Faculty Labor Cost = [Step 7] * Faculty labor hour ratio. Outside Contractor cost = [Step 7] * Outside Contractor labor hour ratio.
9	Staff Hours Required = Staff Labor Cost / Staff hourly wage[2]. Faculty Hours Required = Faculty Labor Cost / Faculty hourly wage. Outside Contractor Hours Required = Outside Contractor Cost / Contractor hourly wage.
10	Bus Cost (Materials and Labor) = [Step 1] – [Step 2].
11	Bus Cost (Labor) = [Step 5].
12	Total Bus Cost (Hardware/Materials/Labor) = [Step 10] + [Step 11].
13	Payload Cost = Expected Payload Cost * 1.30. (30% Margin).
14	Total Flight Unit Cost = [Step 12] + [Step 13].
Notes:	[1] Staff labor hour ratio is the ratio of total staff labor hours for Phase II in Appendix (C) to total hours for Staff/Faculty/Outside Contractors in Phase II. Similarly for Faculty and Outside Contractor. [2] Staff hourly wage based on current NPS Staff Engineer salary converted to FY2003$. Similarly for Faculty and Outside Contractor.

Table 2. NPSat Phase II Cost Algorithm

D. NPSAT-1 COST MODEL INITIAL APPROACH

This section will discuss the initial approach for the NPSat cost model. This approach for the cost analysis of the NPSat program was to use three different methods for estimating satellite costs and then curve fit the results to give an estimation on the price for each program phase. These methods were:

1. CBS: Each subsystem manager would be responsible for acquiring vendor quotes with Rough Order of Magnitudes (ROM) for each component and required spares for their respective subsystem. Then, a "bottom-up" compilation of these costs would be calculated to arrive at an estimate for spacecraft bus and payload hardware figures. Labor expenditures would be determined via labor worksheets per program phase completed by NPS staff engineers.

2. Cost modeling software: The NAFCOM and SSCM cost modeling programs would be used for program cost estimation. SAIC provided training materials for their NAFCOM model and a request for a copy of the SSCM model was sent to Aerospace Corporation. Aerospace cost analysts provided one-on-one counseling with the author for their SSCM and provided an advanced copy of this program. The NAFCOM model is more complex than the Aerospace model and would require training to effectively reflect expected expenditures. It should be noted, these two models only calculate the costs associated with Design/Development, (D&D), manufacture, test, and launch. For the NPSat, this would be Phase II: Critical Design through satellite launch. Concept Exploration/Preliminary Design (Phase I), launch vehicle integration, Ground Support Equipment (GSE), ground facility expenditures, and on-orbit operations (Phase III) would not be included in the actual software data. This data would be calculated using inputs from NPSat program management, the Space Systems Academic Group's (SSAG) Administrator, Ms. Shawn Tribe, and staff engineers.

3. CERs: Preliminary rough cost estimates would be calculated by using the CER parametric in mass provided in Equation (I-1). From this equation, with a projected bus mass of approximately 150 kg, this equation resulted in a spacecraft bus cost of $8,765,203 in Fiscal Year 1992 dollars (FY 1992$). Using the inflation factor conversion table, Table (20-1) of Wertz and Larson's "Spacecraft Mission Analysis and Design" (SMAD), this resulted in a bus cost of $12,367,701 (FY 2003$). After reviewing "Reducing Space Mission Cost", the decision was made to discard the use of this parametric due to historical data which indicated the CER relationships usually resulted in an over-inflated cost estimate for small satellites. ("Reducing Space Mission Cost",

Fig. 8-9). The primary reason for the CER's inaccuracy is sampled data which was used to establish the parametric equation was based on large, expensive satellite programs which do not take into account small satellite program philosophy: build versus buy, maximization of Commercial-Off-The-Shelf (COTS) components, reduction of program length, and increased in-house testing. In contrast, the SSCM's historical performance closely mirrored estimated small spacecraft program costs with their actual program expenditures. This resulted in the use of only the CBS, SSCM, and NAFCOM models and ideally reduced the likelihood of an overestimation of cost. In hindsight, the CER in Equation (I-1) was fairly accurate if compared with the computer model results and inputs from industry experts from the National Reconnaissance Office (NRO) and Naval Research Laboratory (NRL).

E. NPSAT-1 COST MODEL ACTUAL APPROACH

The actual approach used for the preliminary cost estimate of NPSat-1 consisted of the following:

1. CBS: The "bottom-up" CBS component ROM estimates fairly closely resembled the actual flight unit hardware figures calculated in the SSCM and NAFCOM programs. However, there was no suitable means to determine labor expenses. We overcame this dilemma by applying the SSCM and NAFCOM labor calculation discussed in Table 2 in reverse. Cost Breakdown Structure values are provided in Appendix (A).

2. SSCM: There were actually two results from this software package: One from Aerospace Corporations Cost Analysts and one from a model performed by using acquired SSCM software by the author. (Aerospace Meeting). The SSCM, as discussed earlier, result was for Phase II hardware and labor. In order to breakout actual labor hours and expenses, bus cost, and total flight unit cost, the algorithm provided below in Table 2 was used for Phase II values with the concurrence of Dr. Book on the spreadsheet calculations provided in Appendix (C). (Book).

3. NAFCOM: SAIC's Cost model was used to provide an alternate computer software source for the cost analysis. This program is used routinely by NASA and USAF satellite systems engineers. A more complex model than SSCM, NAFCOM

provides additional features for operator induced filters to more accurately perform a comparison with the inherent satellite database. These additional features did contribute to the complexity for the first time user and essentially require professional software training from SAIC or personnel who are very familiar with this software. Due to the time limitations in the Preliminary Design Phase, the author opted to account for this complexity via risk factors in the Monte Carlo method. In addition, the author attended a one-day training course at SAIC offices in Huntsville, AL to ensure this unfamiliarity dilemma was alleviated. Although this training was conducted after the initial cost estimate for NPSat, it would prove beneficial for the refined model discussed later in this document. The algorithm listed in Table 2 is compatible with the results from the NAFCOM model.

F. NPSAT-1 COST MODEL RESULTS

Figure 3 illustrates the results of the different methods of modeling with their average. It reflects all costs associated with the development of NPSat for Phase II of the program schedule. It should be reinforced, all model results were evaluated on the complexity of their software and the familiarity of the analyst then input into a Monte Carlo risk assessment subroutine then averaged. (App. B). Also, the Aerospace (NPS) result was attained via an on-site brief from Aerospace personnel at their office in El Segundo, CA and then executed by the author. In Figure 3, notice the model performed by the author is significantly higher than other cost modeling approaches. The primary reason for this gap from the other results is due to an under-confidence in the analyst's knowledge of the software. The Monte Carlo confidence level "High" was used and when compared to a confidence factor of "High+", the actual Flight Unit cost is $10,378,183 vice $13,283,574. Refer to Appendix (B) for actual Monte Carlo multiplication factors.

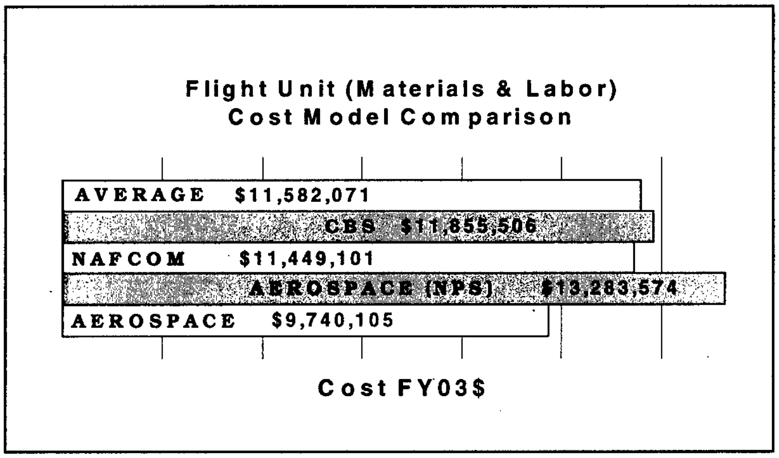


Figure 3. NPSat-1 Flight Unit Cost Comparison.

From these Phase II figures and the algorithm in Table 2, labor hours, labor dollars, and the number of engineering personnel were calculated. Phase I data was easily calculated since this phase covered from Concept Exploration through the actual delivery of the PDR report which coincided with the end of the Summer Quarter at NPS. Actual expense information was provided by Ms. Shawn Tribe, the Administrator for the SSAG, and estimated labor hours were used to arrive at Phase I data that was fairly accurate. Phase III calculations required the use of the Labor Worksheets completed by staff engineers and expected ground facility and operational expenditures. LCDR Tim Anderson was consulted due to his expertise in Operational and Administrative (O&A) cost factors. As a former analyst at the Navy Center for Cost Analysis (NCCA) and a recognized expert at NPS in cost, probability, and risk, he provided a list of expected O&A expenditures which was used in conjunction with the Labor Worksheets to arrive at the expected cost data for Phase III. Figure 4 reflects the expected costs for labor for each phase of the NPSat-1 program.

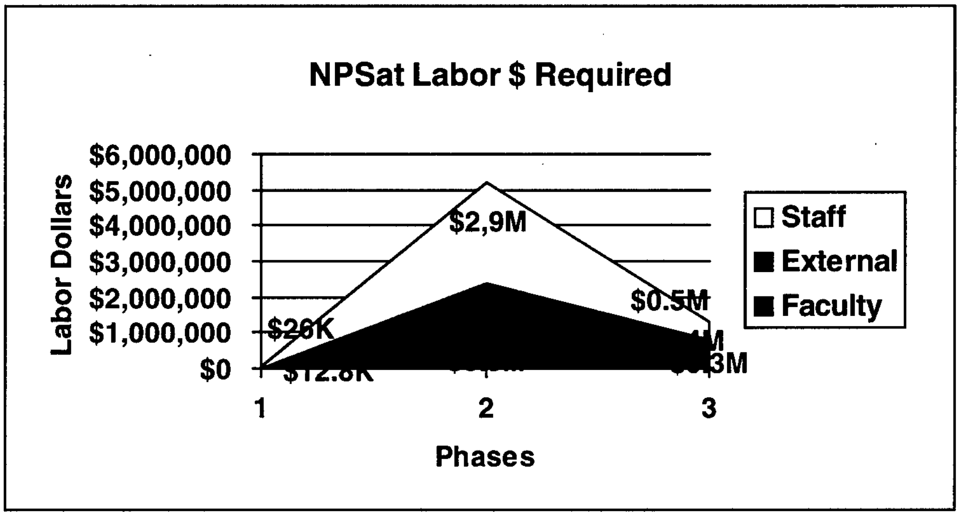


Figure 4. NPSat Labor Dollars Required.

Notice from the data in Figure 4, NPS student labor dollars are not displayed due to our initial ground rule of "free" student labor. The expected labor hours and resultant dollar figure are based on 1500 working hours per year. In addition, the specific hourly wages per type of personnel were $30/hr for staff engineers, $50/hr for faculty, and $70/hr for external engineering personnel. For external personnel, an hourly wage of $50 was used with an additional 40% for indirect costs (overhead and G&A) resulting in a rate of $70/hour in FY 2003 dollars. These indirect costs were based on engineering judgement and will be discussed later in this paper.

Figures 5 and 6 depict the resultant labor hours and number of personnel, respectively. The Figure 5 values were determined from the algorithm discussed in Table 2. From these derived values and from the above mentioned wage rates, the data for Figure 6 was obtained. The number of personnel required was calculated via the known program length with additional schedule margin of 90 days and the projected number of available work hours per staff engineer, faculty member, and external engineer.

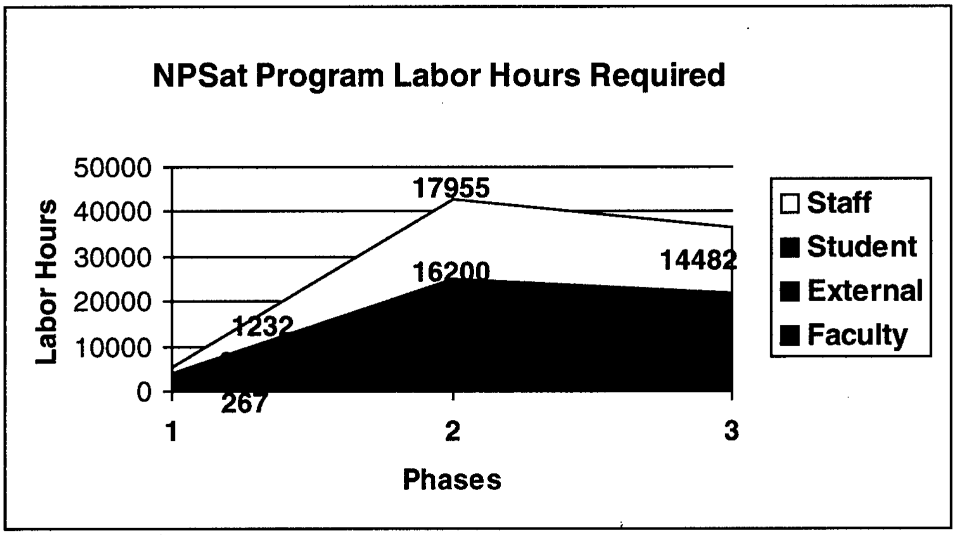


Figure 5. NPSat-1 Labor Hours Required.

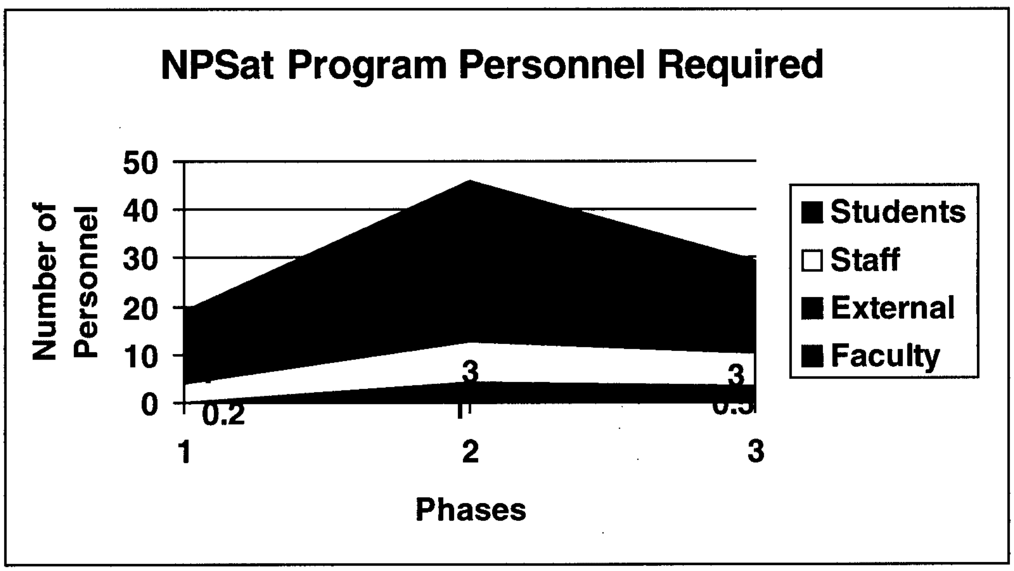
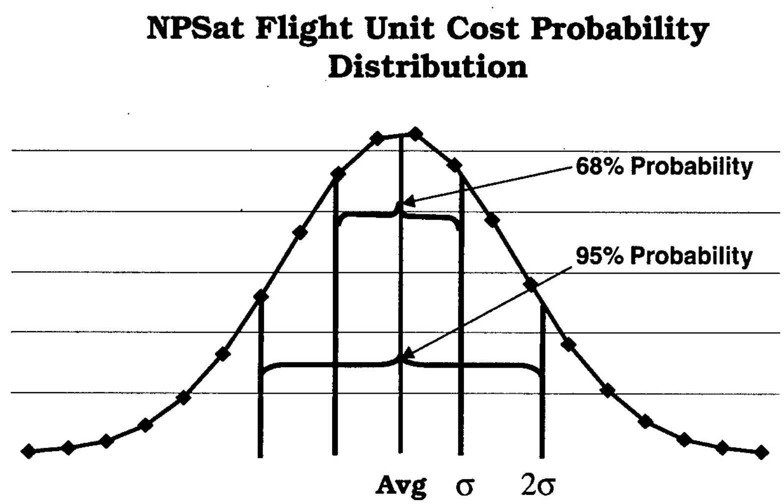


Figure 6. NPSat-1 Number of Personnel Required.

In Figure 6, notice the number of students required is included in the graph. Although there were no labor dollar figures associated with student labor in Figure 4 and no established method of determining the "cost" for a military officer student (the majority of students at NPS are U.S. Military personnel), the labor worksheets accounted for the projected number of students per specific task. These details are provided in Appendix (C).

Once the projected expenditure figures were compiled, the process and actual results were reviewed by LCDR Tim Anderson. He pointed out the necessity for reflecting the probability of realizing these numbers for NPSat Program Management. Figure 7, shows the probability distribution for each Flight Unit cost model projected result from the values previously illustrated in Figure 3.



Average:	$11.6 M	
Standard Deviation (σ):	$1.45 M	
Flight Unit between:	$10.1-$13.1 M	[65% Probability]
Flight Unit between:	$8.7-14.5 M	[95% Probability]

Figure 7. NPSat-1 Flight Unit Cost Probability Distribution.

An itemized list of total NPSat program costs is shown in Figure 8. In addition, the associated expenditures for launch vehicle integration, ground support equipment, and management reserves are included in the diagram. The management reserve is within one standard deviation (one sigma) of the expected cost for a flight unit. Again, all of the

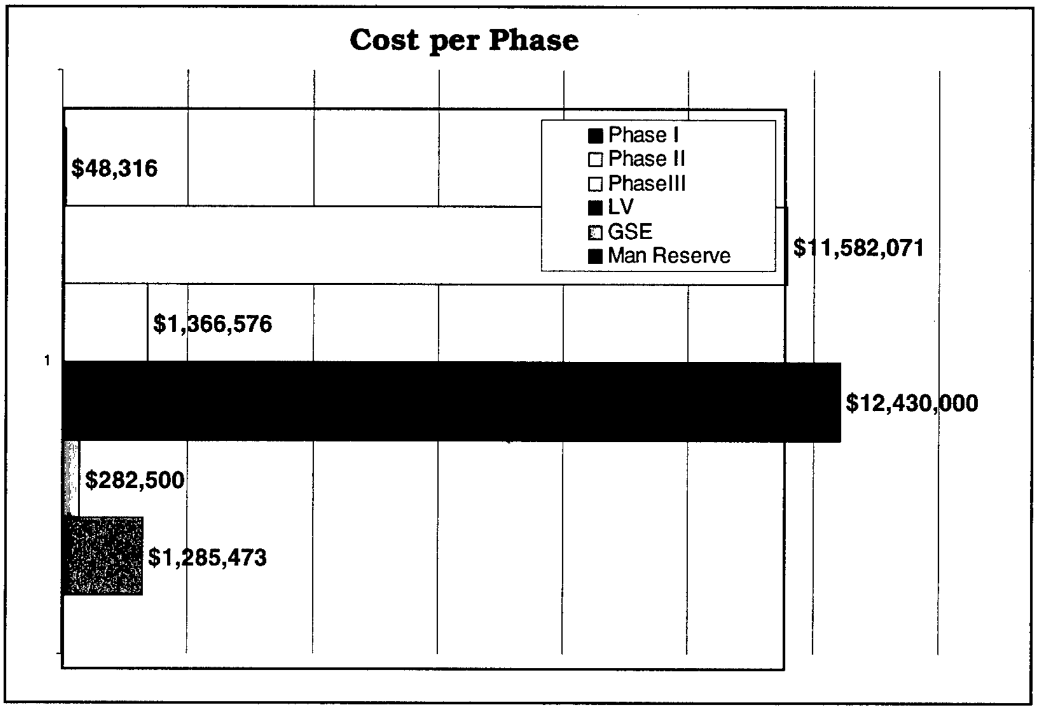


Figure 8. Program Cost per Phase.

calculated values discussed thus far reflected a risk assessment via the Monte Carlo technique.

Ground Support equipment data was calculated through discussions with staff engineers on expected prices for non-flying components essential for the testing and evaluation of actual component which would be integrated into the spacecraft.

III. COMPARISON OF NAVAL POSTGRADUATE SCHOOL SPACECRAFT DESIGN AND DEVELOPMENT CAPABILITIES AND FACILITIES WITH STANFORD UNIVERSITY CAPABILITIES

A. NAVAL POSTGRADUATE SCHOOL SPACE SYSTEM DESIGN AND DEVELOPMENT FACILITIES

As a result of the PANSAT program, the Naval Postgraduate School has emerged as a viable institution for the design and development of small satellites for commercial and military applications. The facilities and equipment dedicated to the development of satellites at NPS consist of the following:

- High precision automated Machining Center (Fig. 9): Vertical Mill, Lathe, 0.0002-inch repeatability, and 20-position automatic tool changer. Performs complex shapes and contours and allows for unique parts fabrication.

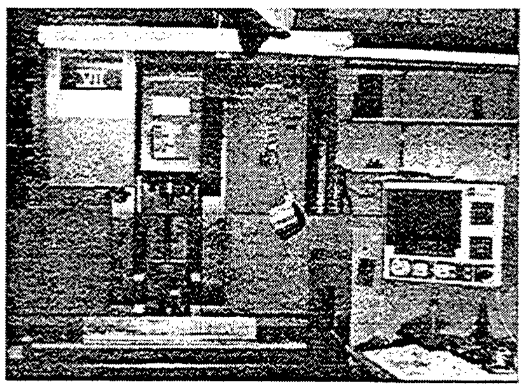


Figure 9. NPS Machining Center

- Soft-walled Clean Room (Fig. 10): Class 10,000. 12' x 10' x 8' (height).

Figure 10. NPS Clean Room.

• Laminar flow bench (clean environment) and Vacuum Oven (Fig. 11):

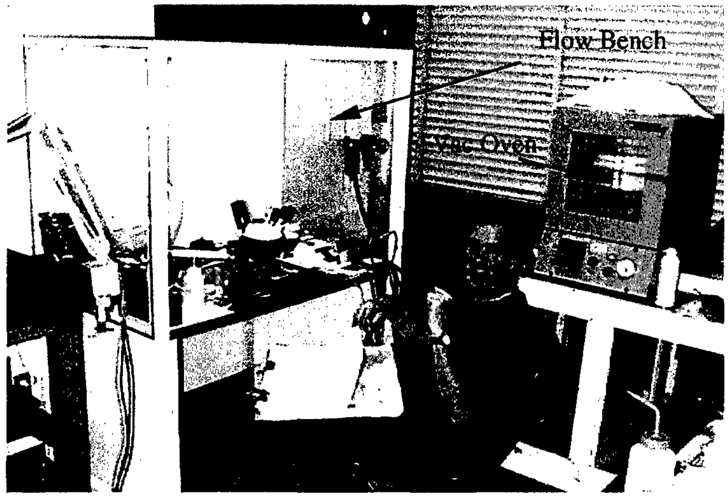


Figure 11. NPS Laminar Flow Bench and Vacuum Oven.

• Thermal-Vacuum Chamber (Fig. 12): Temperature control range of -73^0C to $+177^0$C. One cubic foot test volume. Vacuum up to 7.5 x 10^{-8} Torr. Viewing port and multiple pin connector for in-situ testing.

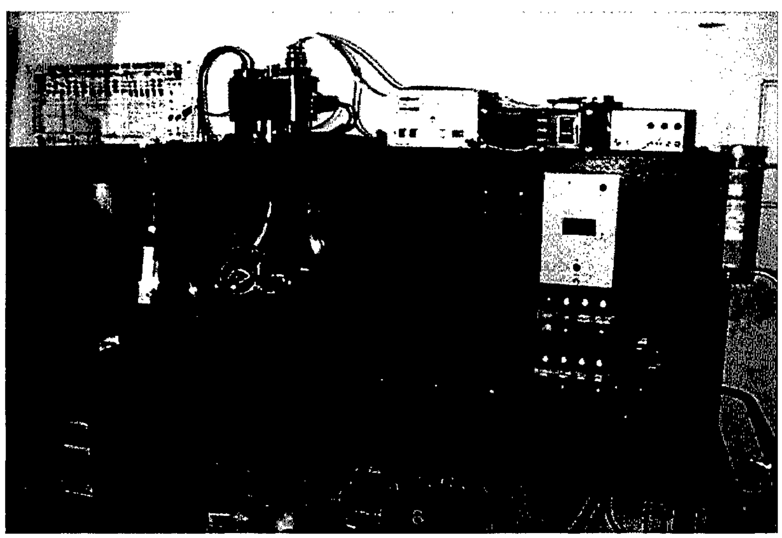


Figure 12. NPS Thermal-Vacuum Chamber.

- Shaker System (Fig. 13): 465 pounds force (Maximum). 93 g's acceleration (Maximum). 1.0 inch double-amplitude displacement. DC - 3.0 kHz frequency range.

Figure 13. NPS Shaker System

- Radio Frequency Shielded Enclosure (Fig. 14): 10' x 8' x 8' (height). Attenuation of 14 kHz (Magnetic) at 60dB, 50 MHz (Electric) at 100 dB, and 10 GHz (Plane Wave / Microwave) at 100 dB.

Figure 14. RF Shielded Enclosure.

- Electronic Test Equipment (Fig. 15): RF testing, Functional testing, In-circuit emulator, and LabView (Test Control).

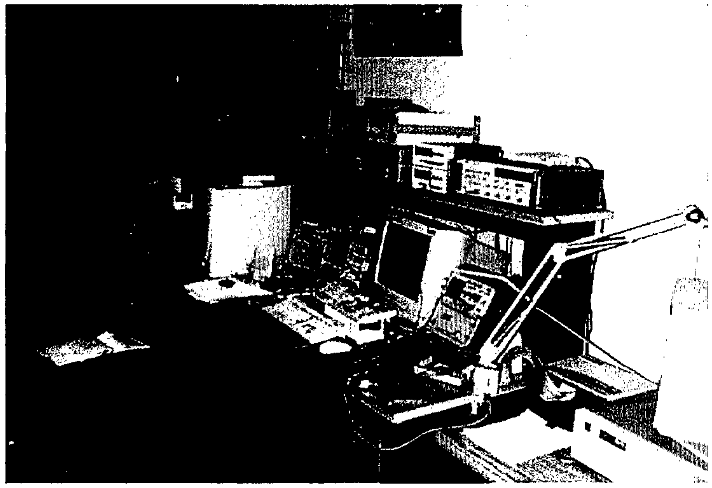


Figure 15. Electronic Test Equipment

- Solar Simulator (Fig. 16): The Solar Simulator 1000 provides equivalent AM0 light in a controlled environment.

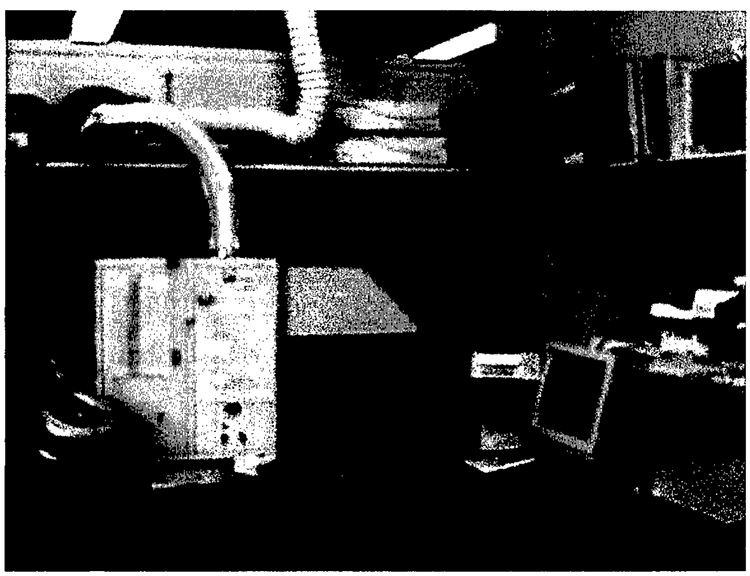


Figure 16. Solar Simulator

- Satellite Operations (Fig. 17): NPS Ground Operations Center provides Staff, Faculty, and Students an interface to satellites on-orbit.

Figure 17. NPS Ground Operations

In addition to the facilities and equipment available for satellite D&D, the following personnel are permanent staff members to the NPS satellite design lab and veterans of the PANSAT program:

- One Aerospace Engineer with experience in systems engineering, structures, mechanical design, orbitology, and vibration/dynamics testing.
- One Computer Engineer with experience in embedded software design, digital logic design, ground station control design, and expertise in C, Assembly, LabView, and Matlab.
- One Electronics Engineer with experience in satellite power electronics, battery design, circuits design (digital and analog), and expertise in C and Matlab.
- One Senior Electronics Engineer Technician with experience in RF communications design, digital logic design, and analog electronics design.

B. STANFORD UNIVERSITY SPACE SYSTEM DESIGN CAPABILITIES AND COMPLETED PROGRAMS

The Stanford University Space Systems Design Lab (SSDL) in Palo Alto, CA was toured in October 1999 by the author. Dr. Robert Twiggs demonstrated the capabilities of the SSDL and discussed the process by which Stanford students design, fabricate, and test their spacecraft. Although Stanford does not have any satellite engineers on staff, it does utilize the labor of Doctoral, Graduate, and Undergraduate students. (Twiggs Interview). The facilities used for satellite design and development are provided in the figures below (SSDL Homepage):

Figure 18. Stanford Clean-Room.

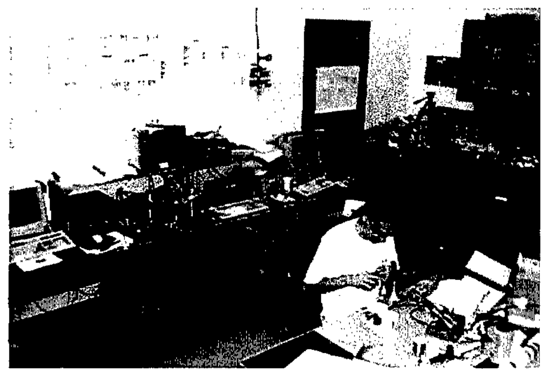


Figure 19. Stanford Main Lab.

Figure 20. Stanford Ground Station.

Stanford's impressive ability to design satellites is highly dependent on the ingenuity of it's undergraduate and graduate students with the added assistance of spacecraft industry "mentors". These mentors meet with students throughout the design effort to provide recommendations to improve the design or to address problem areas encountered during the process. The key to Stanford's success is simplicity of design and spacecraft missions that provide faculty and staff with reasonable objectives and can be incorporated into small buses usually less than 50 kilograms. Examples of this success are the Stanford AudioPhonic PHotographic InfraRed Experiment (SAPPHIRE) and the Orbiting Picosatellite Automatic Launcher (OPAL).

SAPPHIRE was Stanford's first student built microsatellite which was completed on July 10, 1998. It emphasizes simple designs, reasonable objectives, short mission timelines, and the use of COTS equipment to minimize costs. (Twiggs). Students used plywood prototypes constructed via machining equipment on-site and standard power tools. Then the hexagonal structure was fabricated out of honeycomb aluminum. The instruments incorporated into the design were digital camera and voice synthesizer with a virtual sun sensor for a student telemetry experiment and a beacon-based health monitoring system experiment. The spacecraft uses passive magnetic stabilization with permanent magnets mounted to point the camera towards Earth. (SAPPHIRE). Figure 21, shows the SAPPHIRE spacecraft.

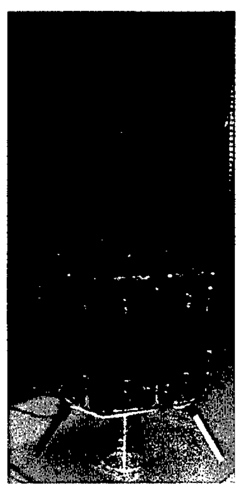


Figure 21. SAPPHIRE Spacecraft. (SAPPHIRE Homepage).

Table 3 shows specific program labor elements.

Program Labor Hours (Thousands)		Personnel Used (for entire program)
Faculty	4.8	3
Doctoral Students	9.6	6
Masters Students	83.2	52
Undergrad Students	9.6	6
External Engineers / Advisors	7.2	15
Note: There may be cases where the same person is used in different phases, however, not enough information is available to break this out in the Personnel field.		

Table 3. SAPPHIRE Labor. (SAPPHIRE Cost Estimation Template).

Program length for SAPPHIRE was approximately 4.0 years. Spacecraft hardware and materials cost was approximately $45,000 with payload integration, overhead, and consulting included in this figure. Total labor hours equated to approximately 114,000 hours for the life of the program.

The OPAL satellite's mission is to demonstrate the feasibility of launching multiple picosatellites from a mothership satellite. OPAL is still awaiting a launch date. The picosatellite launcher ports are in the middle of the picture in Figure 22. Secondary payloads consist of an accelerometer testbed and a magnetometer testbed. Design commenced in early April 1995 with an expected launch to be determined. With a mass of 13.5 kg, this satellite used COTS equipment for batteries, processors, communications, etc. (OPAL). Table 4 shows the labor elements for OPAL. The OPAL spacecraft is pictured in Figure 22.

Figure 22. OPAL outside Stanford's Durand Building during Student Testing. (OPAL Homepage).

Program Labor Hours (Thousands)		Personnel Used (for entire program)
Faculty	4.8	3
Doctoral Students	9.6	6
Masters Students	86.4	54
Undergrad Students	9.6	6
External Engineers / Advisors	7.2	15
Note: There may be cases where the same person is used in different phases, however, not enough information available to break this out in the Personnel field.		

Table 4. OPAL Labor. (OPAL Cost Estimation Template).

Stanford's costs for the OPAL satellite equated to approximately $40,000 with an additional $250,000 donated from other agencies. Total labor hours required were approximately 117,600 hours. Amount donated to the SAPPHIRE program is not available. Scheduled launch date for OPAL is December 7, 1999. (OPAL Homepage).

Satellite testing performed on-site at the SSDL for these two missions consisted of: ambient thermal, shake, and solar simulation for the solar panels.

The advantage of Stanford's simplistic design philosophy for satellites, as Dr Twiggs explained, allows students the ability to learn aspects of spacecraft applied to an actual design. (Twiggs Interview). If we compared the typical Stanford student's curriculum length with that of a NPS student, we would see, the Stanford student will be on campus for a minimum of three to four years. Unfortunately, the NPS Space Engineering or Operations student can expect a maximum of two and a half years. It would be ideal for NPS students to also have the luxury of applying what they learn in class on an actual satellite mission. However, this would require a reevaluation of our satellite design philosophy and would probably require additional program lengths for satellites similar to OPAL and SAPPHIRE in mission and size. There are some lessons learned which can be applied immediately:

- Advisors: Dr. Twiggs indicated the use of industry mentors has provided benefits of sound engineering advice at a minimal cost. Granted, they do not have on staff engineers as NPS, however, the addition of a mentorship program here at NPS would provide an added source of expertise which could help ease some of our staff engineering hours. (Twiggs Interview).
- Smaller Satellites: Stanford limits it's spacecraft to missions which can be successfully accomplished by smaller satellites (less than 50kg). From David Bearden's Dissertation on "A Methodology for Spacecraft Technology Insertion Analysis Balancing Benefit, Cost, and Risk", modern small satellite trends of mass versus cost are approximately $40K/lb in FY 1994 dollars. (Bearden, p. 15, Fig. 2-2). Obviously, the smaller the mass, the lower our expected costs and necessity for a more simple mission. This fact could serve us well here at NPS if we attempt to limit the scope of our missions so we can provide a viable mission with a D&D length within a typical Space Operations or Engineering student tenure of 2.0-2.5 years.
- Donated parts: Any part donated by industry is one less you will have to buy. We must strive to solicit industry for donated parts or labor to reduce cost.

- Commercial-Off-The-Shelf versus Risk: Dr Twiggs indicated the use of COTS versus space rated components does provide some risk in the success of the mission. However, he pointed out, as an educational institution, if the mission fails, what has been lost? (Twiggs Interview). The students had the ability to apply theory to actual design, so is there any actual loss? Granted, if a program uses donated parts in it's design this might not be acceptable to the corporation providing these components. This must be carefully covered in the concept exploration phase to ensure the actual mission is brought to the attention of industry: The successful design and development of a satellite, not necessarily the successful completion of the mission. This should preclude any difficulties in the later phases of the program. Is NPS willing to adapt to this philosophy? This question currently remains unanswered.

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IV. THE NAVAL POSTGRADUATE SCHOOL COST MODEL

A. NPS COST MODEL METHODS

The NPS Cost Model is strictly for cost analysis for satellites designed and developed at the Naval Postgraduate School. A Microsoft Excel based program, this model uses the Cost Breakdown Structure of a satellite, NAFCOM, and SSCM software results as inputs to the program. The inputs are processed through an algorithm which calculates the following:

- Estimated program duration.
- Expected number of personnel required for program.
- Estimated labor hours for program.
- Estimated labor dollars for program.
- Estimated hardware costs.
- Estimated Management Reserves.
- Estimated Overhead, G&A, and Fees.
- Cost per program phase.
- Cost for one flight unit.
- Total program cost estimate.
- Probability of the cost of one flight unit.
- Total program cost spreader.
- Charts for: labor (hours), labor (dollars), number of personnel, probability for cost of one flight unit, fiscal year cost distribution, and total programmatic costs. (App. E).

From this information, the NPS Program Manager can arrive at a cost estimate for the program with adjusted values resultant from a risk assessment performed in the NPS Model. However, the actual cost, or how much NPS will have to pay to realize the satellite program are not calculated. The "price" of any program will depend on many variables which cannot be calculated via one program. For instance, donated components, labor, etc., cannot be accounted for but do have a tremendous impact on how much NPS will have to pay. The NPS Cost Model will be useful during the initial phases of a spacecraft program to perform preliminary cost estimates.

The following inputs are required for the NPS Cost Model (App. D):

- SSCM and NAFCOM resultant total program cost. CBS for satellite bus hardware and spares is also entered in the model. Risk assessment or "Confidence" ratings are also required by the operator on these values to provide risk management.
- Expected program durations and confidence ratings for Phases I, II, and III.
- Expected labor hours for each phase from Labor Worksheets similar to those in the Preliminary Design Report with associated confidence ratings. (Preliminary Design Report, Appendix III-4). These worksheets are supplied in the NPS Cost Model in spreadsheet form.
- Expected personnel salaries in FY 2003 dollars. No confidence ratings are required in this section. Due to the availability of actual salaries it was deemed confidence ratings would not be required.
- Phase III (Post-Launch) other dollar confidence rating. Currently the model assumes 70% for Hardware, Materials, and Supplies, 20% for General and Administrative, Fees, and Maintenance, and 10% for Overhead. These ratios are assumed on a total "Other dollars" total of $50,000 per year for on-orbit operations. This figure was used from discussions with NPS Staff Engineers on expected values for operations. Ideally, the best method for determining this factor would have been to analyze the PANSAT program costs for operations. However, due to the lack of information and the inherent differences of the PANSAT and NPSat programs, there was no concrete method of determining expected operational costs. In addition, there was a

lack of comparison data from on-orbit or successful mission programs which closely resembled NPSat. At this juncture, the $50,000 hypothesis seems well within reason and could be fine tuned in future analysis. Due to the lack of concrete data on operational expenditures expected, these ratios are processed through the Monte Carlo technique via the input confidence ratings for this section.

There were several factors which were determined to be incorrect in the NPSAT-1 Cost Model. The following areas were noted and corrected in the NPS Cost Model:

- In the NPSat-1 cost analysis, labor hours were not processed through the Monte Carlo technique. In addition, a 30% underestimation margin was used an added to each personnel category to arrive at the total labor hours for staff, faculty, external engineers, and engineers. After discussions with Dr. Stephen Book, it was revealed the majority of labor hour estimations are significantly lower than the actual labor hours incurred during the life of a satellite program. For this reason, the author instituted this 30% labor margin as a means to ensure adequate risk management. However, from the Labor Worksheets in the Preliminary Design Report of these total corrected values were not used in the actual labor calculations for Phase I. In addition, none of the labor values from the Preliminary Design Report were processed through the Monte Carlo method. (Preliminary Design Report, App. III-4). This was corrected in the NPS Model to allow for sufficient risk management. Specific new labor values will be discussed later in the Refinement of NPSat-1 Cost Analysis via the NPS Cost Model, Chapter IV, Section B of this paper.
- NPSat-1 analysis labor ratios for the calculation of Phase II labor were incorrect. (Preliminary Design Report, App. III-4). The Phase II values in the Preliminary Design Report Appendix III-4 show Staff Labor of 55% of the total labor, Faculty Labor at 10%, and External Labor at 35% of total labor. This is incorrect. From the Labor Worksheets of this same appendix of the

report, after calculating the ratios of Staff Labor hours / Total Labor hours, Faculty Labor hours / Total Labor hours, Student Labor hours / Total Labor hors, and External Labor hours / Total Labor hours, you arrive at a Staff labor ratio of 60%, Faculty ratio of 8%, Student ratio of 30% and External Engineer ration of 2%. Also, as discussed above, Student Labor dollars were not calculated in the NPSat-1 analysis. This was corrected in the NPS Model by an automatic calculation from the Labor Worksheets which applied the exact ratios per personnel category to the Labor total to arrive at each cost.

- The number of work hours available to each category per year for the NPSat-1 cost analysis was 1,960. After discussion with the NPSat-1 Program Manager, Professor Richard Harkins, Jan Young, the NPS Naval Air Forces (NAVAIR) Chair, and Dean Netzer of the NPS Research Department, this was reduced to a more reasonable level of yearly labor for each personnel category of 1500 hours for the NPS Model. In addition, since the NPS Model now used Student Labor as a parameter, an associated yearly hour estimate for a typical student was required. The chosen value of 500 hours / year / student was selected after discussions with NPS Staff Engineers on their experiences with student assistance (thesis work) from the PANSAT program and from input by the NPSat-1 Program Manager. Typically, a thesis student requires a period of training on the particular subsystem and it's integration within the satellite system. The Staff Engineers indicated the ratio of productive labor hours for Staff-to-Student is approximately 3 to 1. This ratio takes into account the students training time and coursework not directly related to his or her thesis. This means one Staff Engineer hour equals three Student hours. With our use of 1500 hours as the effective work hours per year per Staff Engineer, and using this 3:1 ratio, we arrive at 500 hours per year per Student. If we analyze the 500 Student hours an alternate method, we can assume the student can only contribute during the last two quarters of the curriculum, then in 24 weeks, assuming 4 hours per day, 5 days a week, the student can provide

480 hours per year. Of course, this value does not include the training time required to ensure productivity. So, the 500 hours, is a good estimate for what can be expected as Student Labor available per year. This value should provide a solid basis from which to derive the number of students required for each particular phase of the satellite program. Additional research in this area is required to more accurately reflect the expected number of labor hours one student can contribute to the development effort.

The NPS Cost Model should provide Staff and Management personnel a flexible and user-friendly tool for estimating the cost of a satellite program. Launch Vehicle costs and Launch Vehicle Integration costs are not calculated in this model. There are too many variable and too numerous launch vehicles to effectively provide a calculation for these expenditures.

B. REFINEMENT OF NPSAT-1 COST ANALYSIS

After completion of the design of the NPS Cost Model, the author performed another analysis of the NPSat-1 program through this model. The exact numbers for the Aerospace, NAFCOM, and Cost Breakdown Structure results were used as inputs. In addition, all the above stated required inputs for the NPS Cost Model were supplied from the initial cost analysis. (Preliminary Design Report). The changes incorporated into this analysis were the following:

- Labor: The Program Manager and Staff Engineers were once again consulted to review and refine the initial Labor Worksheets. (App. D, pp. 1-3). The resultant labor values are listed in Table 5. For Phases I and III, labor hours are calculated directly from the Labor Worksheets. Phase II uses the algorithm in Table 1 to determine labor hours. From Table 5, Phases I and III remain relatively unchanged. Highlighted values indicate significant changes from the original estimate. However, if we observe the labor hours for Phase

II, there is a dramatic decrease in the required labor for this phase. There are a couple of contributing factors to this decrease:

1. The labor ratios discussed earlier in this paper for the initial model were incorrect. After recalculating these values, the original ratios did not actually reflect the ratio of the specific personnel cost per total cost. This value is crucial to determine the number of labor hours. This discrepancy was corrected in the NPS Cost Model.

2. The wage for each personnel category was significantly different between the preliminary analysis and the final model. This was due to the use of direct costs only, or "base" salaries for Staff, Faculty, and External personnel of \$30/hr, \$50/hr, and \$70/hr, respectively. In our algorithm labor hours are determined by dividing the personnel category labor dollars by the appropriate wage. For our NPS Cost Model analysis, we used the Indirect Costs and Accelerated Costs in addition to the base salary. Significantly higher wages of \$65/hr for Staff, \$129/hr for Faculty, and \$129/hr for External. When these numbers are used as the divisor, there is a noticeable decrease in the required hours. Basically, in the initial model, our labor hours are less "expensive" than what is typically charged by the university and industry.

3. The initial model dollars were processed through our risk assessment methodology in addition to our wages. We then used these risk corrected values to calculate the number of labor hours. Keep in mind, these labor hours are now "risk assessed". We then took these labor hours and processed them through the Monte Carlo matrix. This is incorrect. The risk assessment on our resultant value had already been accomplished via the model dollars and wages. Essentially, we misused the Monte Carlo matrix resulting in more elevated values.

Preliminary Design Report Labor Hours (In Thousands)					NPS COST MODEL Labor Hours (In Thousands)			
Phase	**Staff**	**Faculty**	**External**	**Students**	**Staff**	**Faculty**	**External**	**Students**
I	1.23	0.27	0.0	3.91	1.32	0.285	0.0	3.74
II	71.82	8.71	26.1	20.4	51.06	5.41	1.14	25.6
III	14.48	5.33	7.80	8.84	14.86	5.73	8.66	8.66

Table 5. Comparison of PDR and NPS Cost Model Estimates for Labor.

- Staff and Faculty wages: The wages used for NPS Staff and Faculty in the preliminary cost analysis do not account for indirect costs and accelerated labor costs. This was part of the ground rules from the estimate listed in the Preliminary Design Report. This is incorrect. In order to accurately account for all dollars associated with labor, the indirect and accelerated costs must be incorporated. This is due to the fact that the SSCM and NAFCOM models account for these figures and therefore, the resultant program cost will be higher. In order to accurately reflect labor, the author met with the Dean of Research at NPS, David Netzer and discussed these issues. The "price" of using NPS Faculty members is these Indirect costs added to the Accelerated costs. Indirect costs are recovered for administrative and facilities support and Accelerated labor costs incorporate leave and fringe benefits for Faculty and Staff personnel. Dean Netzer revealed for costing purposes for prospective research by NPS solicited by outside agencies, NPS assumes an average base salary of $100,000 per year for Faculty and $36,000 for Staff. However, the Staff salary is for administrative personnel. Actual Staff Engineer base salaries average approximately $50,000 per year, per Ms. Shawn Tribe of the Space Systems Academic Group at NPS. The base salary for these engineers was used vice the staff (administrative) values. The basis for using the higher value is the fact that the majority of staff labor dollars expended will be for these engineers. From this point forward, we will assume "Staff" wages refer to the engineer associated wages , unless specifically denoted otherwise. The actual labor cost is determined by adding the total of Accelerated labor and Indirect Labor to these averages. The "charged" Indirect costs are 28% of the base salary and Accelerated costs are 43% of the base. (Memoranda 1 and 2). The result is a yearly wage of $100,000 * 1.71 for Faculty and $50,000 * 1.71 for Staff members. This yields Faculty and Staff yearly wages of $171,000 and $85,500, respectively. In addition, from our discussion, Dean Netzer revealed NPS assumes 214 available work days per year with eight hours per day of labor yielding 1,720 hours per year. There are 260 workdays in the year if we exclude Saturdays and Sundays. Of these possible workdays, NPS assumes 44 are leave, holiday, etc., yielding 214 actual workdays. The initial NPS model assumed 1,960 hours per year with Staff wages of $30/hour and Faculty wages of $50/hour. Upon the author's judgement and with concurrence of the NPSat Program Manger, this was corrected in the NPS Model to 1,500 hours per year to account for worst case. Using these values this yields hourly wages for Faculty and Staff of $114/hour and $57/hour in FY 1999 dollars, respectively. Providing for inflation to FY 2003 dollars, the wages are $129/hour for Faculty and $65/hour for Staff. It is assumed External wages are relatively equal to Faculty wages and Student wages for a junior grade military officer are similar to the Staff (administrative) wages. At $36,000 / year in FY 1999$, multiplied by our Accelerated and Indirect Costs factor of 1.71, this yields a value of $61,560. This value divided by our assumed hours of 1,500 yields a wage in FY 1999 dollars of $41 /hr. Inflated to FY2003$, we arrive at $46 / hr for Students.

- Other Dollars: In the initial estimate, Fees, Overhead, General and Administrative costs for supplies and facilities were not realistic with current figures in the industry. From the NAFCOM model, Contingency (Management Reserve), Program Support (facilities, supplies, support personnel), and Fees can be calculated for each specific cost model. This feature was not used in the initial or the final estimates, but for follow on models is highly recommended. These "other dollars" typically account for 15-30%, 5-10%, and 10-15%, respectively, of the Phase II dollars (NAFCOM model, Systems Engineering section). Applying these ratios to the preliminary model we arrive at "other dollars" of approximately $5.0 million. However, if we look at our calculations used in the initial model for NPSat, the "other dollars" equate to approximately $1.2 million, or $3.8 million below what SAIC corporation recommends for these expenditures (Preliminary Design Report, Appendix III-4). In the refined model with the "new" wages for NPS personnel and External engineers, the applied ratios for "other dollars" come to approximately $2.2 million. Still short of what we should typically expect in industry. However, since these "new" wages now include some of the "other dollars" with the addition of Indirect and Accelerated costs, a noticeable total labor dollar increase is noticed in the realm of $2.9 million. Adding these two figures gives us a total other dollar figure of approximately $5.1 millions which is more realistic (App. E).

- Monte Carlo technique: Transparent to the observer, in the initial estimate for NPSat, there were instances when hypothesized values were run through the Monte Carlo technique twice (Preliminary Design Report, Appendix III-4). Essentially this results in an extra multiplication factor which is exaggerated for lower confidence values. This is an incorrect use of the Monte Carlo method and could result in an overestimation. This was corrected in the NPS Cost Model to ensure if two different categories of estimates were used for a calculation, the resultant was not processed through the Monte Carlo matrix. It is inherent in the technique that if values X and Y are used in a calculation Z which is a function of these X and Y values, and X and Y are analyzed for risk factors, then the resultant value Z will already have an integrated risk correction. In the first cost estimation for NPSat, the resultant value Z, already corrected for risk, was then processed through the Monte Carlo matrix. Specific equations which used this incorrect technique are in the Preliminary Design Report, Appendix III-4, Phase III. In addition, the question was raised by Jan Young as to the validity of using a Minimum multiplication factor for all confidence ratings of 1.0. Ms. Young's question stemmed from the fact that these multiplication factors would not prevent an overestimation. Basically, should the initial estimate on some value be a "worst case" value, then the Minimum multiplication factor would not allow for the case in which the initial estimate was actually higher than the actual result. (Young Interview). From correspondence with Fred Raymond, he explained the initial "guess" for values should be the "best case." If this is the case, then the likelihood of overestimation is minimized which should alleviate the requirement for a Minimum multiplication factor less than 1.0.

- Student Labor: Student Labor was determined to be "free" in the initial cost estimate. It could be debated this is not actually correct. Some accounting of cost for the effort students exert into all program phases should be performed. For the Refined Model, Student Labor was again essentially "free", however a different approach was used to demonstrate this idea. Student salaries were equated with Staff salaries and included benefits as noted in our discussion of Accelerated and Indirect Costs. These wages were used to calculate the cost of this labor for the duration of the program and then subtracted from the overall total labor dollars required to indicate the perceived "price" of the student labor from a budget standpoint. Basically, NPS will not have to pay students to work on the satellite, so the "price" of their effort is essentially "free."

- External Labor: Due to proprietary information, an average value from different satellite corporations for engineer wages was unobtainable, so the author used an equivalent value to the cost of Faculty labor which did not seem unrealistic. This value, $129/hour FY 2003, was deemed appropriate by Aerospace and NAFCOM cost analysts. (NAFCOM Training Course and Book Interview).

- Fiscal Year Cost Distribution: A new feature incorporate into the NPS Cost Model, this distribution is generated via the Navy Center for Cost Analysis' (NCCA) "Inflation Indices and Outlay Profile Factors" for Research, Development, Test, and Evaluation for Phases II and III. This document was supplied by Tim Anderson after he was consulted on a possible method of implementing a cost spreader. The requirement for a cost spreading technique was generated after Professor Chris Olsen's request for a breakout of dollars per phase. Initially, the method used by SAIC corporation via a Beta Distribution was chosen as a possible candidate method. Tara Clayborn of SAIC provided the "Funding Allocation Tables and Beta Distribution Estimating Software" handbook as a reference. The software program referenced in this handbook is used by NASA personnel for "cost spreading" their satellite programs. Tim Anderson suggested the use of the Navy's method via the NCCA's document discussed above. The use of this method vice the beta distribution was based on the likelihood the NPSat program would be funded by the Department of the Navy. In hindsight, the use of both of these methods would have provided a more robust reference for determining the anticipated costs per fiscal year.

The NPS Cost Model developed by the author was used for the refined cost analysis for NPSat-1 with the following highlights listed in Table 6.

All Dollars FY 2003	Initial Model	Final Model
Spacecraft Bus	$4,176,856	$3,633,828
Spacecraft Payload	$440,700	$440,700
Labor[1]	$8,252,235	$6,835,743
Other Dollars (Fees, Overhead, etc.)	$127,173	$2,190,744
Ground Support Equipment	$282,500	$282,500
Management Reserve (5% of Flt Unit)	$1,285,473	$756,600
Expected Program Cost (not including Launch Vehicle & LV integration).	$14,564,937	$14,140,115
[1]Labor does not include cost of Student labor. This figure has already been subtracted out.		

Table 6. Initial Versus Final Model Program Costs

If we notice the Spacecraft Bus cost, the NPS Cost Model resulted in a Bus cost actually lower than the original estimate. This was due to multiple uses of the Monte Carlo matrix in the original model. As discussed earlier, this was not necessary, and obviously contributed to a higher forecast cost for the spacecraft's bus.

In addition to these values, the following Tables depict the expected cost of labor or Labor Dollars (Table 7), and Personnel required (Table 8) compared with the initial NPSat-1 model performed during the preliminary design.

Labor Dollars (FY 2003 Dollars K)	Initial Model			Final Model		
PHASES	I	II	III	I	II	III
Staff	26.6	2,706.0	478	85.71	3,318.6	966.1
Faculty	12.8	492.0	309	36.78	439.23	725.97
External Engineers	0	1,722.0	406	0	146.41	1,116.9
Students[1]	NA	NA	NA	171.93	1,178.2	398.27
Total	39.4	4920	1193	294.42	5,082.4	3,207.2

[1]Student Labor Dollars were not calculated in the initial model for Phase I,II, and III.

Table 7. Initial Model Versus Final Model Labor Dollars.

In Table 7 above, notice the dramatic increase in expected labor dollars for the Final Model. This is primarily due to the inclusion of Student Labor dollar figures and the "new" addition of Indirect Costs and Accelerated costs in the final estimate.

Personnel Required	Initial Model			Final Model		
PHASES	I	II	III	I	II	III
Staff	0.63	8.67	7.0	1.64	6.79	4.25
Faculty	0.18	1.0	0.5	0.36	0.45	1.61
External Engineers	0	2.0	3.0	0	0.15	2.47
Students[1]	15	32.4	19.0	13.97	10.22	7.42
Total[2]	15.81	44.07	29.5	15.97	17.61	15.75

[1]Phase II and Phase III values are the number of personnel per year.

Table 8. Initial Model Versus Final Model Personnel Required by Phase.

In Table 8, notice 10.22 students required per year for Phase II versus our initial model that shows 32.4 students for the entire Phase II length of 5.0 years. Essentially, we will require 5.0 * 10.22 or approximately 50 students for the entire length of Phase II. This is not unrealistic if we consider for the PANSAT spacecraft over 30 thesis students conducted research on the satellite. However, after discussing expected throughput of Space Operations and Space Engineering students with Lisa Quidileg, the Educational Technician for the Office of the Registrar at NPS, there may not be enough students in these curricula to provide the expected labor. Per Ms. Quidileg, the following are expected numbers of students per year for Space Systems Operations and Space Systems Engineering:

- Space Systems Engineering (Curriculum 591): There are currently 27 students on board NPS. Ms. Quidileg indicated in her discussions with the Director of Admissions, Mr. Ted Calhoun, the expected numbers for the 591 curriculum are 12 students per year. Expectations are for a single entry into the curriculum in September, if this holds true, for a curriculum length of approximately 2.25 years, we should expect a total of approximately 24-36 Space System's Engineering students enrolled at one time. If we assume 15% of these students have NPSat related thesis topics, then we will have 4-6 students per year.
- Space Systems Operations (Curriculum 366): The expected numbers for future 366 classes will be 10 students per year. With a curriculum length of approximately 2.0 years, we can expect 20 students enrolled at one time. Again, using a 15% value for thesis work, approximately 3 Space Operations students will be available for labor per year. The 15% factor is based solely on judgement by the author and should provide the maximum expected number of thesis students. (Quidileg Interview).

The expected total will be 7-9 thesis students per year. This presents quite a dilemma if we assume our Student Labor values required for NPSat are accurate. The following recommendations are provided to solve this problem:

- Utilize applicable classes to provide assistance in the design and development of the NPSat. As an example, for the Space Power and Radiation effects class, EO 3205, students in this class could receive "hands-on" experience with NPSat's solar cells and Electrical Power Subsystem.
- Institute the use of industry "mentors" as discussed earlier in Stanford's use of these experts. These mentor help reduce "growing pains" in the design process and provide a measure of relief for the Staff Engineers and Students.
- Use other NPS curriculum students for labor. Electrical and Mechanical engineering students can provide a wealth of research and labor towards the NPSat program. Computer Science students can assist Staff Engineers in developing hardware and software. In addition, Systems Management, Operations Analysis, and Financial Management students can assist Program Management and Staff Engineers in analyzing System Engineering, Cost/Budget, Management, Reliability, Integration and Testing issues.
- Reduce the scope of NPSat's mission. A reduction in mission requirements will lead to a reduction in fiscal requirements, labor, parts, etc. This is the only alternative if we assume our labor estimates are fairly accurate.

If we do not attempt to augment our student hours generated by prospective thesis students, by our estimates, we will fall significantly short of the hours required for student labor. From our projection of required students, we will fall short of required labor by approximately 2-4 students per year.

C. REDUCING THE NPSAT-1 PROGRAM BUDGET

Throughout the preliminary design process, the student engineer design team focused on improvements to minimize mass, power, cost, and complexity. The following areas of impact are provided:

- Employ body-mounted solar arrays: For the NPSat-1 design team, body-mounted arrays were a goal from day one. However, the power requirements for the payloads are too large to use Silicon body mounted arrays. The use of body mounted arrays has the following benefits:
    1) Reduces spacecraft mass by 14 kg by eliminating the hinge and panel release mechanisms.
    2) Reduces the cost by at least $100,000. ROM figures for these mechanisms per Appendix (A) demonstrate the hardware alone will save in excess of $100,000 in Fiscal Year 99 dollars. There will be additional savings realized for labor which has yet to be determined.
    3) Increases the reliability of the spacecraft. See Appendix (XIV) of the Preliminary Design Report.
    4) Simplifies the design.
    5) Simplifies testing which saves on labor costs.

  Possible detriments include:
    1) Generates less power which may force use of more expensive Galium Arsenide (GaAs) solar cells or the deletion of payloads from the mission.
    2) Solar arrays will be hotter which reduces the solar cell efficiency.
    3) Increased internal thermal temperatures will have an impact on the thermal control scheme of the spacecraft.
- Use GaAs Solar Cells: The current design uses Silicon (Si) cells. The use of GaAs cells provides the following benefits:
    1) Increased power availability.
    2) Better performance at the expected higher array temperatures.

3) Cells suffer less radiation degradation which extends their life.
4) Makes the use of body mounted arrays more achievable.

The main detriment is their higher cost of 2 to 5 times that of Si Cells, or approximately, and additional $200,000 - $400,000 (FY 1999) dollars.

- Use Lithium Ion (Li-Ion) battery offered by Eagle Picher: This proposal works only under the assumption we receive free Li-Ion batteries from Eagle Picher. Benefits include:
  1) Free battery saves approximately $120,000.
  2) Mass savings of approximately 3 kg.
  3) Li-Ion perform better at expected spacecraft internal temperatures.

  Detriments include:
  1) New technology with increased mission risk and possible lower reliability.
  2) Unknown length of acquisition timeline compared with more readily available Nickel Cadmium (NiCad) cells.
  3) Li-Ion batteries also demand more stringent charge control necessitating increased electronics.
  4) Li-Ion cells currently do not have the same cycle lifetime as other space-rated batteries.
- Remove the Global Positioning System (GPS) receiver: The current NPSat-1 design employs a GPS receiver to provide orbit and clock data. From the PDR on 15 September and a meeting with NRO personnel on 28 September 1999 in Chantilly, Virginia, we are not convinced the GPS is required to receive clock and orbit information. Benefits of removing the GPS include:
  1) Mass reduction of 1.6 kg.
  2) Power reduction of 4.7 W peak / 0.5 W average.
  3) Saves approximately $200,000.
  4) Removes antennas which allows more surface space for possible solar cells or thermal radiators.

Possible detriments include:

1) Lack of accurate ephemeris to correlate the auroral images to the desired accuracy.
2) Removes high accuracy timing signal.

The orbital and timing data along with the pointing knowledge of the spacecraft are crucial to accurately correlate the images to their actual physical location. NRO personnel are convinced, from the above meeting, passive methods of determining ephemeris and providing clock data can be used to alleviate the necessity of GPS on the satellite.

- Reduce the overall size of the spacecraft: As we discussed in Chapter I, spacecraft mass is linked to cost. However, we cannot directly use the parametric for mass in Equation (I-1) from our discussions earlier. Trade studies must be conducted to explore how NPSat-1 spacecraft mass is linked to cost and success of the mission.
- Lower the downlink rate: The transponder in the NPSat preliminary has a ROM cost of $500,000. Lowering the downlink rate may decrease the cost and complexity but will have an impact on the amount of mission data that can be collected. This reduction will probably require an increase in the number of ground stations. This is an area which requires detailed analysis and could possibly be future thesis project. (Preliminary Design Report).
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In addition to these recommendations for possible cost reduction, there are additional means in which to lower the actual cost of the program:

- Free components: Dr. Bob Twiggs of the Space Science Design Laboratory at Stanford University routinely acquires free payloads and components from industry. Routinely space companies "fly" these components to provide an opportunity to test hardware in the actual space environment which yield (if they operate successfully) a means of acquiring parts which can be marketed as space-rated. The free Eagle Picher battery discussed above is a direct example.

- Free Labor: Any opportunity a satellite program has to incorporate free labor for different aspects of the program yields obvious cost savings. For the NPSat program, NRL and NRO personnel have a wealth of knowledge in the design, manufacture, integration, and testing of satellites. Accessing these resources will have an impact in reducing the cost of a satellite. Following Stanford's use of industry mentors will also aide in reducing labor costs.
- Free Testing: Testing and Integration of a satellite can lead to schedule slippage and unanticipated cost overruns. Again, accessing the NRO and NRL resources for finding free testing facilities will allow for a reduction in the price of the program.
- Free "Ride": The launch vehicle integration and vehicle costs for the NPSat program are above $12,000,000. The versatility of the design for incorporation into any vehicle will greatly increase the opportunity for a free ride.
- Risk: As discussed earlier, Stanford is willing to accept increased risk as long as it is able to achieve it's ultimate goal of completing the design of a spacecraft through student labor. COTS equipment and "old-fashioned" ingenuity in design do increase the risk, but dramatically reduce the cost. This cost savings is imperative for a satellite developed at a learning institution in the age of reduced budgets.
- Partnerships: Partnerships with other institutions has multiple advantages, the division of budgetary obligations, access to additional facilities and equipment, and increased educational opportunities. In addition, these partnerships help create a liaison between institutions staff, 'faculty, and students. More robust missions can be tackled leading to higher interest from the satellite industry and government agencies.

- Reduce the scope of the mission: Reducing the mission requirements or spacecraft necessary capabilities leads to a more simple design which makes achieving the new mission objective more realizable.

V. SUMMARY

A. NPS COST MODEL

The NPS Cost Model is a unique cost model which may provide great insight into satellite D&D costs for Naval Postgraduate School staff, faculty, and students involved in a spacecraft program. It is absolutely mandatory, that detailed tracking of fiscal expenditures, labor hours, and personnel required be performed. If the NPSat spacecraft is indeed designed to be a modular bus intent for reuse, this tracking will provide a baseline for future cost analysts and program managers from which valuable lessons could be drawn. As discussed earlier, the only method we have to determine the accuracy of the cost model is through this tracking and future comparison with actual expenditures.

There are many areas which require continued analysis in order to optimize the capabilities of the NPS Cost Model:

- Follow on research should include travel to various universities with satellite programs similar to NPS. Detailed examinations of these universities methods of cost modeling and their actual costs must be conducted. Through observations of the methodology of these other institutions, we can gather information on what we can expect to encounter through our program life.
- Additional commercially available cost modeling software programs should be used as resources. An increase in the number of sources of program costs will only enhance the cost model. Great care must be observed to ensure the techniques discussed in the algorithm in Table 2 apply to any additional sources. This may require tailoring the algorithm to conform.
- The values for calculating Phase III Operations and Maintenance (O&M), or "Other Dollars", should be reevaluated. The author used $50,000 / yr as a rough estimate due to a lack of concrete data from industry. Tim Anderson was consulted to ensure the ratios used to calculate Overhead, Maintenance,

Fees, Supplies, etc., were within reason. Follow-on research should seek to gain more concrete data from industry and other educational institutions to ensure these ratios are indeed realistic. Ideally, a thorough evaluation of institutions with similar facilities, equipment, and spacecraft would be conducted to determine a scaling factor which would apply to our environment here at the Naval Postgraduate School.

- The number of External Engineers required for Phase II seems unrealistic. In Table 8, 0.15 External Engineers are estimated per year for Phase II. On the authors judgement solely, this value seems low and should be analyzed to ensure the estimated labor hours required for External Engineers in the Labor Worksheets is valid. This could be done by conferring again with the Staff Engineers, Program Management, and other industry experts.
- The Monte Carlo technique used by the author was based on inputs from Fred Raymond 's article referenced earlier. This risk assessment is crucial, however, a reexamination of the implementation of Mr. Raymond's technique is required. The method, as discussed earlier, does not account for instances in which the analyst may have overestimated. Granted, this is rarely the case, as discovered from discussions with Dr. Book and other experts in the spacecraft industry. However, what if this were the case in our estimate? There would be no way to recover the actual values which may be below the "Minimum" value calculated via the matrix in Appendix (B). Tim Anderson and Jan Young both recommend reevaluating the implementation of this technique to perform a "normal" Monte Carlo analysis which will prevent the above dilemma from occurring. A possible follow-on technique would require evaluating each "figure" to determine the expected distribution of values and to process this figure via available risk assessment software such as CRYSTAL BALL. This software program gives the user the ability to perform numerous random distributions on s specific figure to determine what the "most likely" expected value.

- More research is required in determining which fiscal year cost spreading technique (Beta Distribution, Outlay Profiles, etc.) is more applicable for inclusion in the model. An evaluation of NPSat's funding line will lead to the source for fiscal dollars and then provide the analyst with a better understanding of which method is appropriate.

NPS should eventually be able to arrive at a dedicated CER specific to our institution which would be the result of heritage of the NPSat program models. This would provide a rapid method of calculating costs very early in the program. Of course, this assumes a long line of satellites using the NPSat bus.

B. REEVALUATING NPS' SATELLITE DESIGN AND DEVELOPMENT PHILOSOPHY

It is imperative, that NPS continue to strive to provide satellite design and fabrication opportunities for NPS personnel for a more enhanced education. Crucial to this objective is identifying satellite missions that are within the limits of our institution from a fiscal and capability standpoint. The success Stanford University has in it's spacecraft production provides a good lesson for us to possibly follow. Stanford's small satellite design philosophy is similar to Surrey Satellite Technology Limited (SSTL). SSTL was formed in 1985 as a company wholly owned by the University of Surrey located in Guildford, England. Their objective is to exploit academic research within the University's Space Centre to develop and market cost-effective small satellites for rapid and affordable commercial access to space. The engineers at SSTL have accumulated many years of comprehensive experience and in-depth knowledge in cost-effective satellite engineering. Granted, SSTL's staff and facilities are more robust than Stanford, but their philosophy is basically the same: Produce cost-effective small satellites. (SSTL). Surrey has demonstrated that extremely low-cost missions can be achieved by starting cost reduction before selection of mission goals. For many mission managers in inflexible programs, this is probably an unattainable luxury; for managers faced with fixed budgets and more flexible orbital aspirations, however, their techniques of selecting mission objectives to fit available resources will work very well. An example of Surrey's success is Portugese Satellite or PoSAT launched from French Guyana in 1993 onboard an Ariane vehicle. This 50 kg microsatellite carried five payloads for technology demonstration and engineering research. SSTL built the satellite for the Portugese PoSAT Consortium as a part of a technology transfer program. SSTL managed PoSAT-1's design, construction, and in-orbit operations, so the Consortium could quickly and inexpensively enter into satellite engineering. From the initial contact between the two groups, to the end of the post-launch commissioning phase, this program lasted 21 months and cost $2.6 million. Although this mission carried several complex payloads, is supported by a highly redundant and flexible bus. (Wertz and Larson, "Reducing Space Mission Cost", pp 551-553). Their success has lead to SSTL winning numerous contracts from Korea's KITSAT, U.S. Air Force's MightySat 11.1, to DBS Industries for the development of a constellation of satellites to target hard-to-locate utility meters. Recently, Surrey's UoSAT-12 was launched from an SS-18 from Kazakhstan in April 1999. This was the first satellite launched from a vehicle which was once one of the world's most power intercontinental ballistic missiles (ICBM). (SSTL Press Release). A direct example of Surrey's innovative and somewhat risky approach to satellite development and delivery.

NPS should incorporate this philosophy and push the "envelope" in developed spacecraft technology and missions. Future NPS programs should incorporate propulsion, more sophisticated ADCS systems, tracking solar arrays, and scientific experiments that are designed by NPS faculty and students. Above all, the ingenuity of NPS staff, faculty, and students will be decisive factor in making this transition successfully.

The current curriculum at Naval Postgraduate School for Space System Operations and Space Systems Engineering students, is designed to prepare graduates as future program managers for the Department of Defense. The integration of class work with an actual satellite program that students can actively be involved in from start to completion is achievable and should prove to enhance this process.

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APPENDIX A. NPSAT-1 PRELIMINARY DESIGN COST BREAKDOWN

Spacecraft Payload	ROM($99)	ROM($03)	Power (W)	Mass (kg)
LWIR Imager	GFE	GFE	25.00	8.0000
VIS Imager	200.000	226.000	10.00	5.0000
Dosimeter	GFE	GFE	5.00	3.1751
Electron Spectrometer	100.000	113.000	2.00	3.0000
Subtotal	300.000	339.000	42.00	19.1751
Spacecraft Bus	**ROM($99)**	**ROM($03)**	**Power (W)**	**Mass (kg)**
Structure:				
Top Deck	500.00	565.00	NA	3.34
Mid Deck	500.00	565.00	NA	3.34
Bottom Deck	500.00	565.00	NA	3.34
Face 1	500.00	565.00	NA	1.28
Face 2	500.00	565.00	NA	1.28
Face 3	500.00	565.00	NA	1.28
Face 4	500.00	565.00	NA	1.28
Face 5	500.00	565.00	NA	1.28
Face 6	500.00	565.00	NA	1.28
Longerons	500.00	565.00	NA	5.11
Lower LV Adaptor	Incl w/LV	Incl w/LV	NA	5.00
Upper LV Adaptor	Incl w/LV	Incl w/LV	NA	5.11
Subtotal	5000.00	5650.00	NA	32.92
Structure Spares:				
Full Structure	5000.00	5650.00	NA	3.34
Spares Subtotal	5000.00	5650.00	NA	3.34
Structures Total	10000.00	11300.00	NA	36.26
Spacecraft Bus	**ROM($99)**	**ROM($03)**	**Power (W)**	**Mass (kg)**
ADCS/GNC:				
Magnetometer	7.000	7.910	1.00	0.12
Star Tracker	130.000	146.900	2.00	0.80
WFOV Sensor 1	75.000	84.750	0.06	0.11
WFOV Sensor 2	75.000	84.750	0.06	0.11
NFOV Sensor 1	75.000	84.750	0.06	0.28
NFOV Sensor 2	75.000	84.750	0.06	0.28
GPS	200.000	226.000	0.50	1.56
Reaction Wheel	20.000	22.600	6.50	1.27
Torque Rod X	14.500	16.385	0.53	0.43
Torque Rod Y	14.500	16.385	0.53	0.43
Torque Rod Z	14.500	16.385	0.53	0.43
Subtotal	700.500	791.565	11.83	5.82
ADCS/GNC Spares:				
WFOV Sensor	75.000	84.750	0.06	0.11
NFOV Sensor	75.000	84.750	0.06	0.28
Magnetometer	7.000	7.910	1.00	0.12
Torque Rod	14.500	16.385	0.53	0.43
Reaction Wheel	20.000	22.600	6.50	1.27
Spares Subtotal	191.500	216.395	8.15	2.21
ADCS/GNC Total	892.000	1.007.960	19.98	8.02

	FY99$	FY03$
Payload	300.000	339.000
Structure	10.000	11.300
ADCS/GNC	892.000	1.007.960
CD&H	100.265	113.299
EPS	471.931	533.282
TT&C	500.000	565.000
Thermal	25.000	28.250
Mechanisms	90.380	102.129
Flight Unit TOTAL	2.389.576	2.700.221
20% ROM Margin	477.915	540.044
Total for Bus & Payload	2.867.491	3.240.265

Spacecraft Bus	ROM($99)	ROM($03)	Power (W)	Mass (kg)
CD&H:				
Chassis	2,000	2,260	-	13
386 Processor (2)	6,000	6,780	12.5	5.0
RS-422 Quad Line Drive (2)	3,000	3,390	-	-
DRAM(2)	7,000	7,910	-	-
SRAM	1,500	1,695	-	-
EEPROM (2)	3,600	4,068	-	-
EDAC SRAM (2)	8,000	9,040	-	-
DMA Controller (2)	8,000	9,040	-	-
Data Formatter	3,000	3,390	1.0	2.5
Adv Control Unit EPS	3,000	3,390	4.0	4.0
Adv Control Unit ADCS	3,000	3,390	1.0	4.0
RS-422 Dual Line Driver	2,000	2,260		
CMOS Mux (4)	52	59	-	-
Glue Logic (2)	1,000	1,130	-	-
Current Sensors (10)	40	45	-	-
DC/DC Converters (2)	200	226	-	-
MOSFETs (24)	1,200	1,356	-	-
Diodes / Caps / Resistors	1,780	2,011	-	-
Volt References	120	136	-	-
Bidirectional Transceiver	7,500	8,475	-	-
Octal Bus Latch	7,500	8,475		
Buffers / Binary Counters	3,000	3,390	-	-
CD&H Subtotal	72,492	81,916	18.5	28.5
CD&H Spares:				
386 Processor	3,000	3,390	6.25	2.5
RS-422 Quad Line Drive	1,500	1,695	-	-
DRAM	3,500	3,955	-	-
SRAM	1,500	1,695	-	-
EEPROM	1,800	2,034	-	-
EDAC SRAM	4,000	4,520	-	-
DMA Controller	4,000	4,520	-	-
Data Formatter	3,000	3,390	1	2.5
Adv Control Unit EPS	3,000	3,390	4	4
RS-422 Dual Line Driver	1,000	1,130		
Mux	13	15	-	-
Sensor/Resist/Caps/Diodes/etc	1,460	1,650	-	-
Spares Subtotal	27,773	31,383	11.25	9
CD&H Total	100,265	113,299	29.8	37.5
Spacecraft Bus	**ROM($99)**	**ROM($03)**	**Power (W)**	**Mass (kg)**
Power:				
Power Control Unit	4,000	4,520	-	0.80
Battery	120,000	135,600	-	19.00
SA1	45,933	51,904	-	1.53
SA2	45,933	51,904	-	1.53
SA3	45,933	51,904	-	1.53
SA4	45,933	51,904	-	1.53
SA5	45,933	51,904	-	1.53
SA6	45,933	51,904	-	1.53
Cabling	2,000	2,260	-	5.00
Power Subtotal	401.598	453.806	-	33.98
Power Spares:				
Power Control Unit	4,000	4,520	-	0.80
Solar Array (1)	45,933	51,904	-	1.53
Battery (4 cells)	20,000	22,600	-	2.00
Cabling	400	452	-	0.50
Spares Subtotal	70,333	79,476	-	4.83
Power Total	471,931	533,282	-	38.81
Spacecraft Bus	**ROM($99)**	**ROM($03)**	**Power (W)**	**Mass (kg)**
TT&C:				
Tx / Rcv Antenna 1	25,000	28,250	0	0.23
Tx / Rcv Antenna 2	25,000	28,250	0	0.23
Transponder	400,000	452,000	1.05	2.27
Miscellaneous	50,000	56,500	5	0.91
TT&C Subtotal	500,000	565,000	6.05	3.64
TT&C Spares:				
None	0	0	0	0
TT&C Total	500,000	565,000	6.05	3.64
Spacecraft Bus	**ROM($99)**	**ROM($03)**	**Power (W)**	**Mass (kg)**
Thermal:				
Insulation / Coatings	20,000	22,600	0	0
Thermal Subtotal	20,000	22,600	0	0
Thermal Spares:				
Insulation / Coatings	5,000	5,650	0	0
Spares Subtotal	5,000	5,650	0	0
Thermal Total	25,000	28,250	0	0
Spacecraft Bus	**ROM($99)**	**ROM($03)**	**Power (W)**	**Mass (kg)**
Mechanisms:				
Documentation	1,200	1,356	0	0
Frangibolt(6)	18,000	20,340	1	0.08
Hinge Units(6)	58,440	66,037	0	3.46
Mech Subtotal	77,640	87,733	1	3.54
Mech Spares:				
Frangibolt	3,000	3,390	1	0.08
Hinge Unit	9,740	11,006	0	3.46
Spares Subtotal	12,740	14,396	1	3.54
Mech Total	90,380	102,129	2	7.08

APPENDIX B. MONTE CARLO CONFIDENCE LEVELS

Confidence Level	Code	Minimum	Most Likely	Maximum
Very High (High+)	VH	1.0	1.04	1.10
High	H	1.0	1.06	1.15
Moderate to High (Mod+)	MH	1.0	1.09	1.24
Moderate	M	1.0	1.14	1.36
Low to Moderate (Low+)	LM	1.0	1.20	1.56
Low	L	1.0	1.30	1.85
Very Low to Low (V.Low+)	VLL	1.0	1.46	2.31
Very Low	VL	1.0	1.68	3.01

Example: For a value of 2.5 with a Moderate to High (MH) confidence level..

Minimum Value = 2.5 * (1.0) = 2.5
Most Likely Value = 2.5 * (1.09) = 2.725
Maximum Value = 2.5 * (1.24) = 3.10

Then take Average = 2.775

The expected value of 2.5 given a confidence of this estimate of Moderate to High is 2.775.

APPENDIX C. NPSAT-1 PRELIMINARY DESIGN REPORT CALCULATIONS

1. NPSAT-1 PRELIMINARY DESIGN PHASE I CALCULATIONS

PHASE I

	Actual
LABOR (HOURS)	
Staff	950
Faculty	267
External	0
Total (Labor Hours)	**1,217**
LABOR (DOLLARS)	
Staff	26,600
Faculty	12,816
External	0
Total Labor (Dollars)	**39,416**
OTHER (DOLLARS)	
Management	5,000
Overhead	NA
Fees	NA
G&A	3,700
Hardware/Materials	NA
Testing	NA
Software	200
Total Other (Dollars)	**8,900**
TOTAL Dollars Phase I	**48,316**

2. NPSAT-1 PRELIMINARY DESIGN PHASE II CALCULATIONS

PHASE II

COST MODELS	Aerospace	Aerospace (NPS)	NAFCOM	CBS	Average
Model Results (FY03$)	27,046,520	30,811,344	20,510,000	21,601,767	
Monte Carlo Confidence Rating	High+	High	Low	Very Low+	
Min	27,046,520	31,207,504	20,510,000	21,601,767	
Most Likely	28,128,381	32,660,025	26,663,000	31,538,580	
Max	29,751,172	35,433,046	37,943,500	49,900,082	
Average	**28,308,691**	**33,100,191**	**28,372,167**	**34,346,810**	**31,031,965**

LABOR (DOLLARS) [PHASE II]	Aerospace	Aerospace(NPS)	NAFCOM	CBS	Average
Labor with Single Contractor (85%)	24,062,387	28,135,163	24,116,342	29,194,788	
Labor for University Environment (30% of 85%)	7,218,716	11,254,065	9,646,537	11,677,915	
Reduction Factor for inhouse Testing (30%)	2,165,615	3,376,220	2,893,961	3,503,375	
Labor Subtotal	**5,053,101**	**7,877,846**	**6,752,576**	**8,174,541**	**6,964,516**
Includes Maint/Overhead/Fees/G&A					
5% Maintenance	252,655	393,892	337,629	408,727	
10% Overhead	505,310	787,785	675,258	817,454	
5% Fees	252,655	393,892	337,629	408,727	
5% G&A	252,655	393,892	337,629	408,727	
Maint/Overhead/Fees/G&A Subtotal	**1,263,275**	**1,969,461**	**1,688,144**	**2,043,635**	**1,741,129**
Staff/Faculty/External Labor for Phase II	**3,789,826**	**5,908,384**	**5,064,432**	**6,130,906**	**5,223,387**
Staff (55%)	2,084,404	3,249,611	2,785,437	3,371,998	2,872,863
Faculty (10%)	378,983	590,838	506,443	613,091	522,339
External (35%)	1,326,439	2,067,934	1,772,551	2,145,817	1,828,185

LABOR (HOURS) [PHASE II]	Aerospace	Aerospace(NPS)	NAFCOM	CBS	Average
Staff	52,110	81,240	69,636	84,300	71,822
Faculty	6,316	9,847	8,441	10,218	8,706
External	18,949	29,542	25,322	30,655	26,117
Total	77,376	120,630	103,399	125,173	106,644
LABOR (Hours) for PHASE II / Year					
Staff	13,028	20,310	17,409	21,075	17,955
Faculty	1,579	2,462	2,110	2,555	2,176
External	4,737	7,385	6,331	7,664	6,529
Total	19,344	30,157	25,850	31,293	26,661
LABOR (Hours) Available for ONE person / Year					
Staff	1,960	1,960	1,960	1,960	1,960
Faculty	1,960	1,960	1,960	1,960	1,960
External	1,960	1,960	1,960	1,960	1,960
Total	5,880	5,880	5,880	5,880	5,880
PERSONNEL REQUIRED for PHASE II					
Staff	**7**	**10**	**9**	**11**	**9**
Faculty	**1**	**1**	**1**	**1**	**1**
External	**2**	**4**	**3**	**4**	**3**
TOTAL PERSONNEL [EXCEPT STUDENTS]	**10**	**15**	**13**	**16**	**14**

PHASE II	Aerospace	Aerospace(NPS)	NAFCOM	CBS	Average
Satellite Bus Cost (Hardware/Materials)	4,246,304	4,965,029	4,255,825	3,240,265	4,176,856
Satellite Bus Cost (Labor)	5,053,101	7,877,846	6,752,576	8,174,541	6,964,516
Total Bus Cost	9,299,405	12,842,874	11,008,401	11,414,806	11,141,371
Payload Cost + 30% (Hardware/Materials/Labor)	440,700	440,700	440,700	440,700	440,700
Total Payload Cost	440,700	440,700	440,700	440,700	440,700
TOTAL FLIGHT UNIT COST	9,740,105	13,283,574	11,449,101	11,855,506	11,582,071

3. NPSAT-1 PRELIMINARY DESIGN PHASE III CALCULATIONS

PHASE III					
	CBS	Confidence			
LABOR (HOURS)					
Staff	14,482	Low			
Faculty	5,330	Low			
External	7,800	Low			
Total	**27,612**			**Monte Carlo**	
LABOR (DOLLARS)			**Min**	**Most Likely**	**Max**
Staff	$477,906	Low	$477,906	$497,022	$525,697
Faculty	$309,140	Low	$309,140	$321,506	$340,054
External	$405,600	Low	$405,600	$421,824	$446,160
Total	**$1,192,646**		**$1,192,646**	**$1,240,352**	**$1,311,911**
OTHER (DOLLARS)					
Hardware / Materials / Supplies (70%)	79,100	Low			
G&A / Fees / Maint / Travel (20%)	22,600	Low			
Overhead (10%)	11,300	Low			
Total	**$113,000**				
Total Dollars Phase III	**$1,305,646**				

		Phase III	
Monte Carlo Confidence	**Labor Dollars**	**Other Dollars**	**Total Dollars**
Min	1,192,646	113,000	1,305,646
Most Likely	1,240,352	117,520	1,357,872
Max	1,311,911	124,300	1,436,211
Average	1,248,303	118,273	**1,366,576**

ADJUSTED TOTAL DOLLARS PHASE III	**$1,366,576**

APPENDIX D. NPS COST MODEL USER INPUT SCREEN

1. NPS COST MODEL USER INPUT SCREEN, COST MODEL RESULTS AND LABOR WORKSHEET CONFIDENCE

Aerospace	$27,046,520	**VH**
NAFCOM	$20,510,000	**MH**
Cost Breakdown (CBS) Flt Unit H/Ware Only	$3,240,265	**M**

COMPLETE PHASE I,II,III Labor Worksheets first. THEN ENTER CONFIDENCE ONLY.

2. NPS COST MODEL USER INPUT SCREEN, WAGES AND PHASE III OTHER DOLLARS.

Staff	65
Faculty	129
External	129
Students	46

[illegible]
For instance, if you do not think [illegible] other dollars spent [illegible] hardware, etc.
then you would enter the appropriate low confidence level. However, keep in mind
if you expect the percentage to be lower you must either tailor this program or enter
a high confidence. This program always assumes you are underestimating.
If you assume you are overestimating, then the program must be tailored.

[illegible] III OTHER DOLLARS (Launch-Orbit Ops)	Confidence
Hardware, Material, Supplies (70%)	L
O&M Fees, Maintenance, Travel (20%)	M
Overhead (10%)	H

3. NPS COST MODEL LABOR WORKSHEET SCREEN (PHASE I) [INCLUDES INPUTS FOR REFINED NPSAT-1 COST ANALYSIS]

Phase I (Concept Exploration thru Preliminary Design)					
	Labor Hours (in Thousands of Hours)				
System Design	**Staff Engineers / Staff**	**Faculty**	**Students**	**External**	**Remarks**
Structure	0.025	0.010	0.300		
Mechanisms	0.025	0.010	0.200		
ADCS/GNC	0.035	0.010	0.300		
Thermal	0.025	0.010	0.200		
TT&C	0.100	0.010	0.300		
EPS	0.100	0.010	0.300		
CD&H	0.100	0.010	0.300		
Software	0.050	0.010	0.050		
Ground Support Equipment	0.010	0.005	0.002		
Instruments					
VIS Imager	0.000	0.010	0.100		
Electron Spectrometer	0.000	0.010	0.100		
Other					
Bus / Payload Integration	0.005		0.005		
Testing	0.105		0.000		
Msn Dsn / Pln	0.010		0.100		
Data Processing	0.125		0.050		
Data Analysis	0.105		0.000		
Management	0.025	0.100	0.300		
Reliability & QA	0.100		0.040		
Launch Vehicle Sched/Analysis	0.003		0.040		
Mgmt Reserve	0.000				
Totals	**0.948**	**0.205**	**2.687**	**0.000**	**3.840**
30% Underestimate Margin	**0.2844**	**0.0615**	**0.8061**	**0.**	**1.152**
TOTAL	**1.232**	**0.267**	**3.493**	**0.000**	**4.992**

4. NPS COST MODEL LABOR WORKSHEET SCREEN (PHASE II) [INCLUDES INPUTS FOR REFINED NPSAT-1 COST ANALYSIS]

	Phase II (Critical Design thru Mission Readiness Review)				
	Labor Hours (in Thousands of Hours)				
System Design	**Staff Engineers / Staff**	**Faculty**	**Students**	**External**	**Remarks**
Structure	1.200		1.000	0.500	Offbase Fab
Mechanisms	0.600		1.000		
ADCS/GNC	1.800	0.200	1.000		
Thermal	0.800	0.100	0.500		
TT&C	1.000	0.050	0.500		
EPS	1.500	0.050	0.500		
CD&H	2.400	0.050	0.500		
Software	3.000	0.050	0.250		
Ground Support Equipment	1.000	0.050	0.250		
Instruments					
VIS Imager		0.100	1.000		
Electron Spectrometer		0.100	0.500		
Other					
Bus / Payload Integration	1.500				
Testing	0.800	0.100	0.125	0.100	
Msn Dsn / Pln	2.200	0.100	0.125		
Data Processing	1.200	0.100	0.100		
Data Analysis	0.400		0.100		
Management	2.000	2.000	0.100		
Reliability & QA	1.200	0.100	0.100		
Launch Vehicle Integration	0.800		0.100	0.400	
Training	0.400		0.000	0.050	
Mgmt Reserve (35%)	8.330	1.103	2.713	0.368	
TOTALS	**32.130**	**4.253**	**10.463**	**1.418**	**48.263**
TOTAL	**40.460**	**5.355**	**13.175**	**1.785**	**60.775**

5. NPS COST MODEL LABOR WORKSHEET SCREEN (PHASE III) [INCLUDES INPUTS FOR REFINED NPSAT-1 COST ANALYSIS]

Phase III (Launch thru Operations&Support)					
	Labor Hours (in Thousands of Hours)				
	Staff Engineers / Staff	Faculty	Students	External	Remarks
Data Collection	3.000		2.000	3.000	Life of Spacecraft
On Orbit Testing	0.300				2 months
Software Analysis/Eval	0.300		0.250		2 months
Data Processing	3.000	0.150	0.250		
Data Analysis	1.000	0.150	2.000		
Management	1.000	3.000			
Reliability & QA	1.000	0.150			
Training	0.300	0.150	0.200		
Ground Station Maint	0.200	0.150	0.300	3.000	
NPS onsite Maint	0.200	0.150	1.000		.4K Staff hrs Per Year
Mgmt Reserve					
TOTALS	**10.300**	**3.900**	**6.000**	**6.000**	**26.200**
30% Underestimate Margin	**3.09**	**1.17**	**1.8**	**1.8**	**7.86**
TOTAL	**13.390**	**5.070**	**7.800**	**7.800**	**34.060**

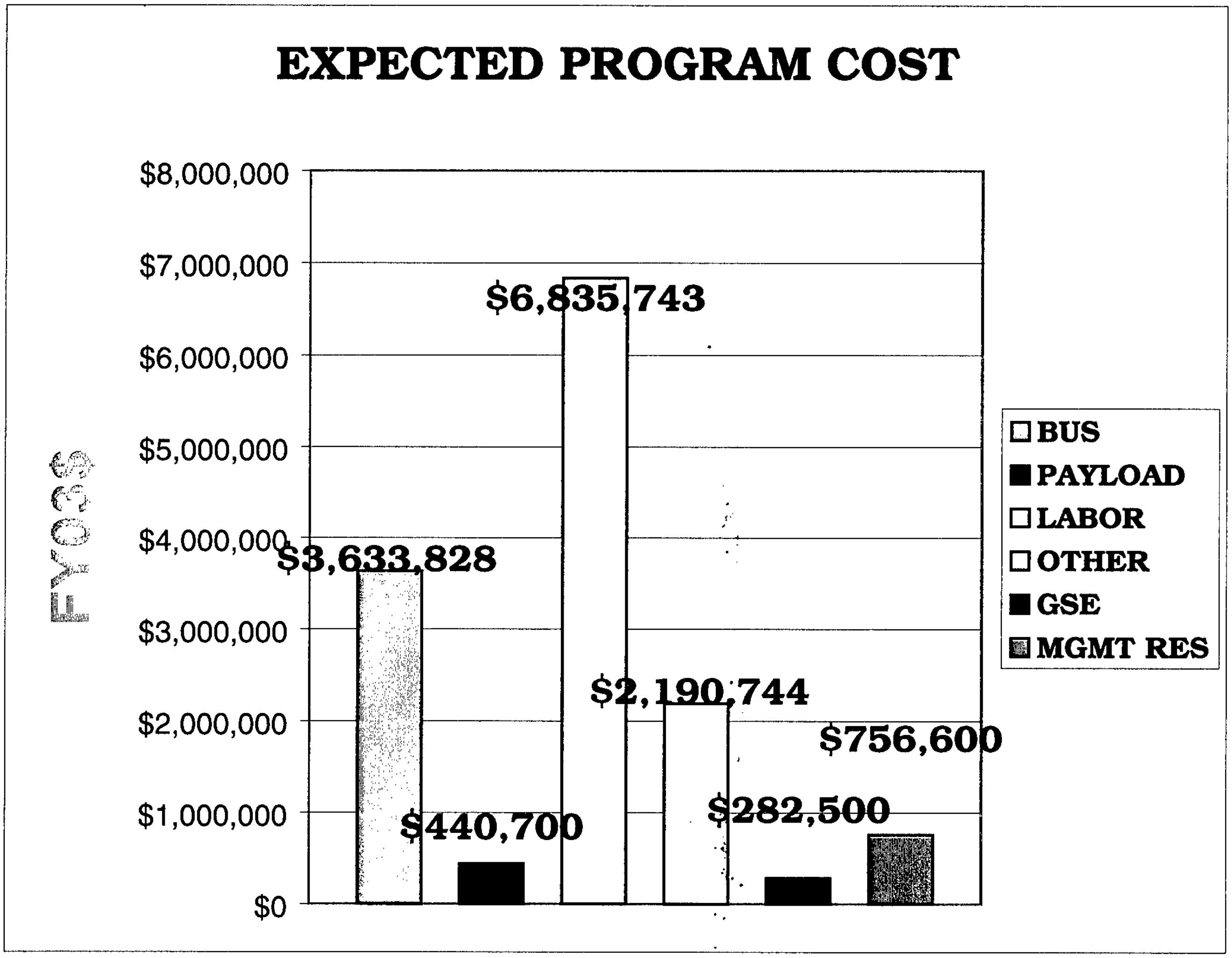
Program Phase:	**Staff Engineers / Staff**	**Faculty**	**Students**	**External**	**Subtotal**
Phase I	1.232	0.267	3.907	0.000	5.405
Phase II	40.63	5.355	20.4	1.785	68.17
Phase III	13.390	5.070	7.800	7.800	34.060
Total	**55.252**	**10.692**	**32.107**	**9.585**	**107.635**

Note: Labor values are processed through the Monte Carlo Matrix in App B.

APPENDIX E. NPS COST MODEL REPORT SCREEN

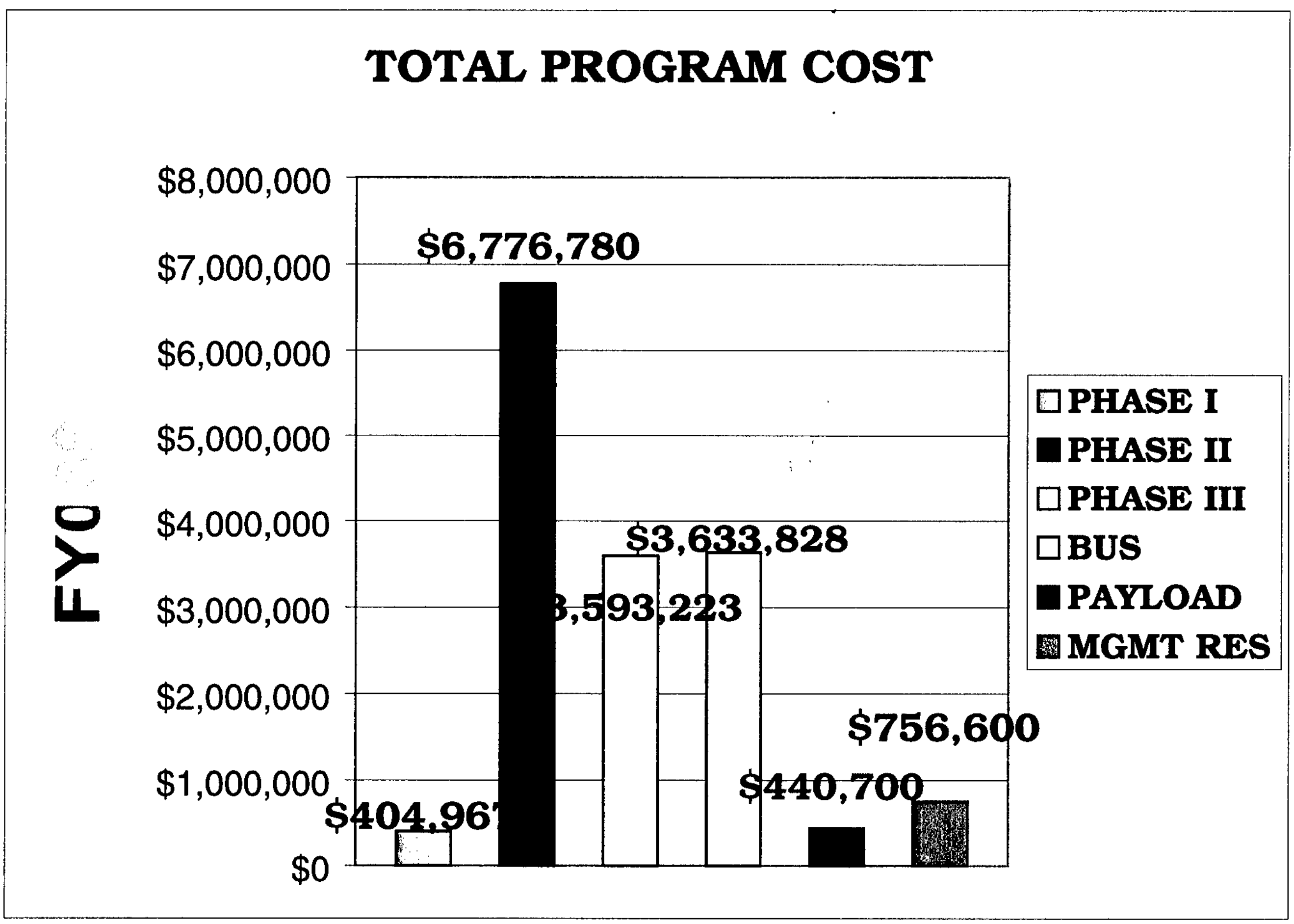
1. REFINED NPS COST MODEL, REPORT SCREEN, EXPECTED PROGRAM COST

EXPECTED PROGRAM COST	FY03 $
Spacecraft BUS	$3,633,828
Spacecraft PAYLOAD	$440,700
Labor (Not Including Student Labor)	$6,835,743
G&A/FEES/etc (Other Dollars)	$2,190,744
GSE	$282,500
MANAGEMENT RESERVE (5% FLT UNIT)	$756,600
EXPECTED PROGRAM COST $	$14,140,115



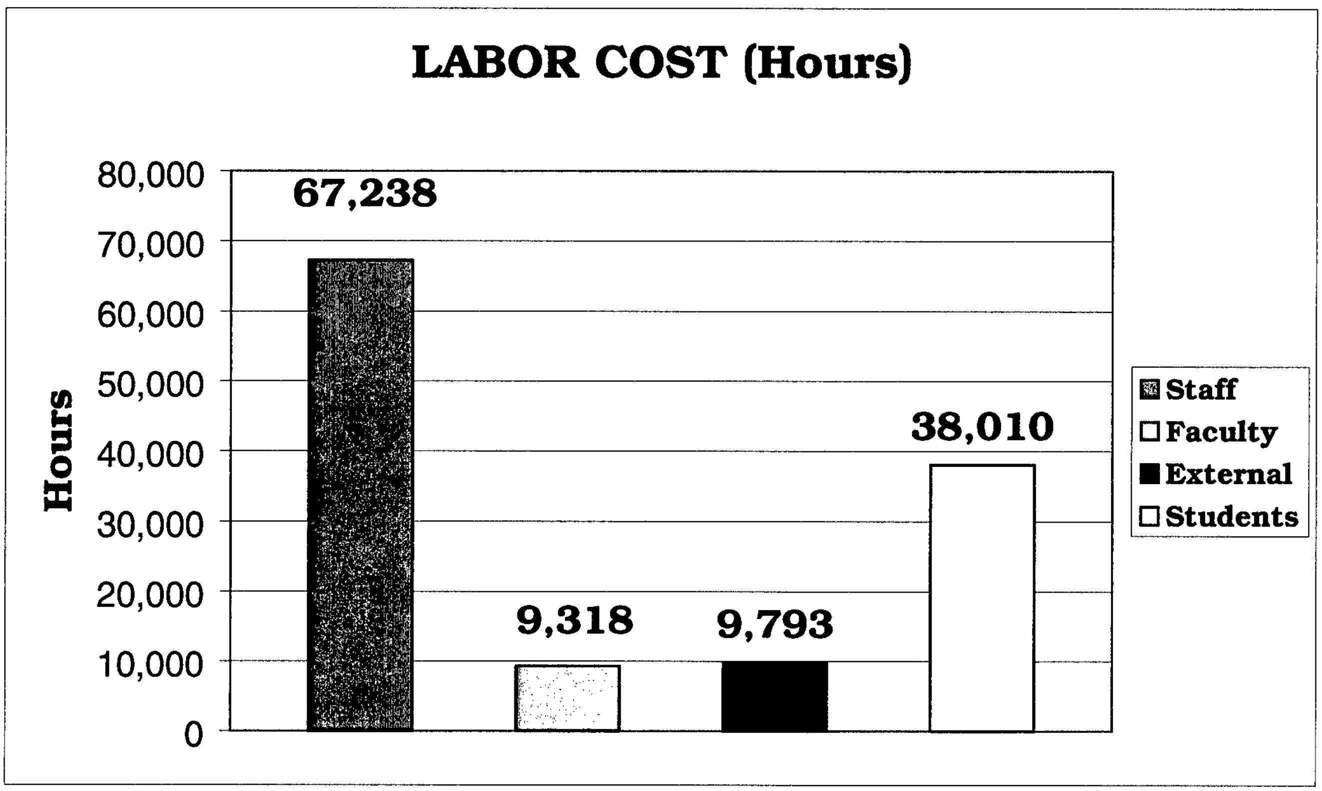
2. REFINED NPS COST MODEL, REPORT SCREEN, TOTAL PROGRAM COST

TOTAL PROGRAM COST	FY03 $
TOTAL PROGRAM COST	$15,888,597



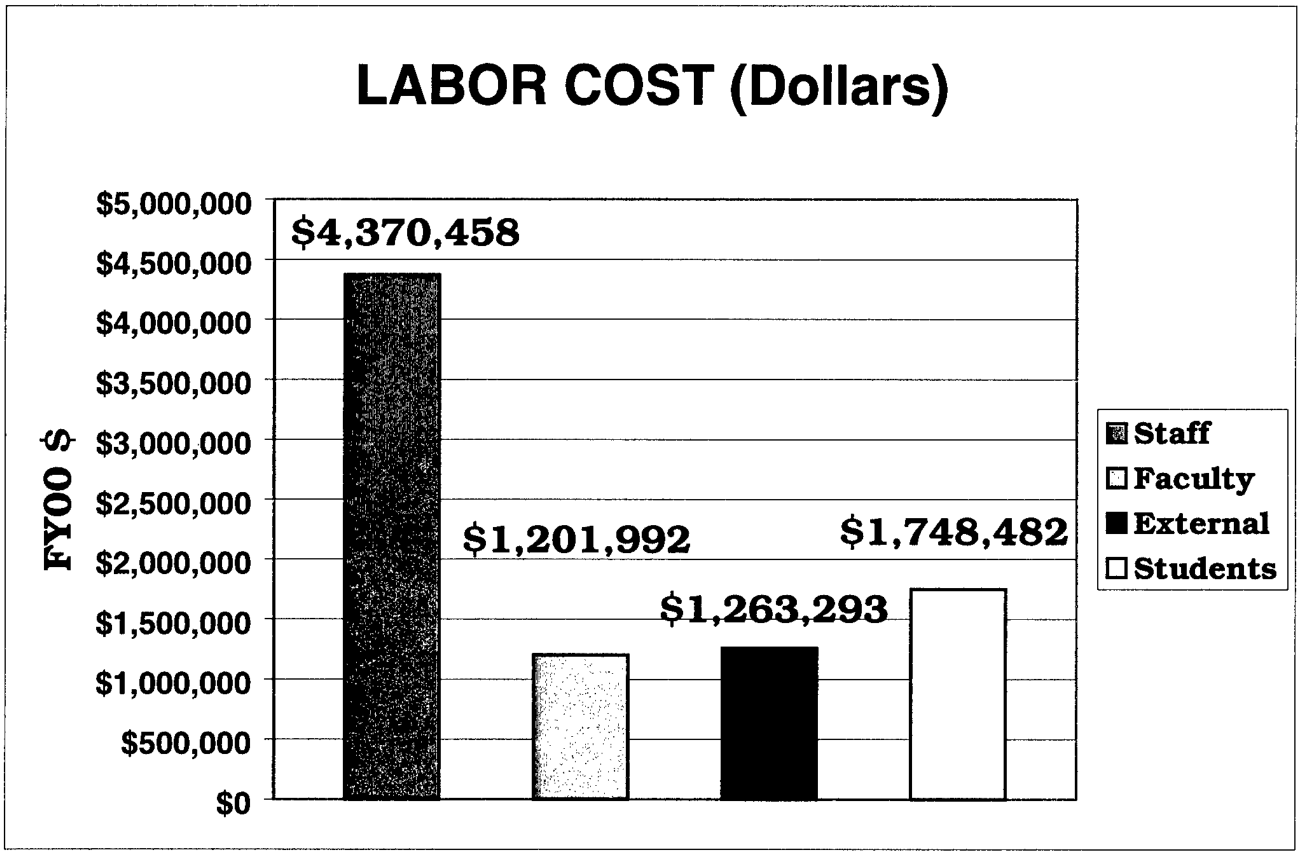
3. REFINED NPS COST MODEL, REPORT SCREEN, LABOR HOURS REQUIRED

Staff	67,238
Faculty	9,318
External	9,793
Students	38,010

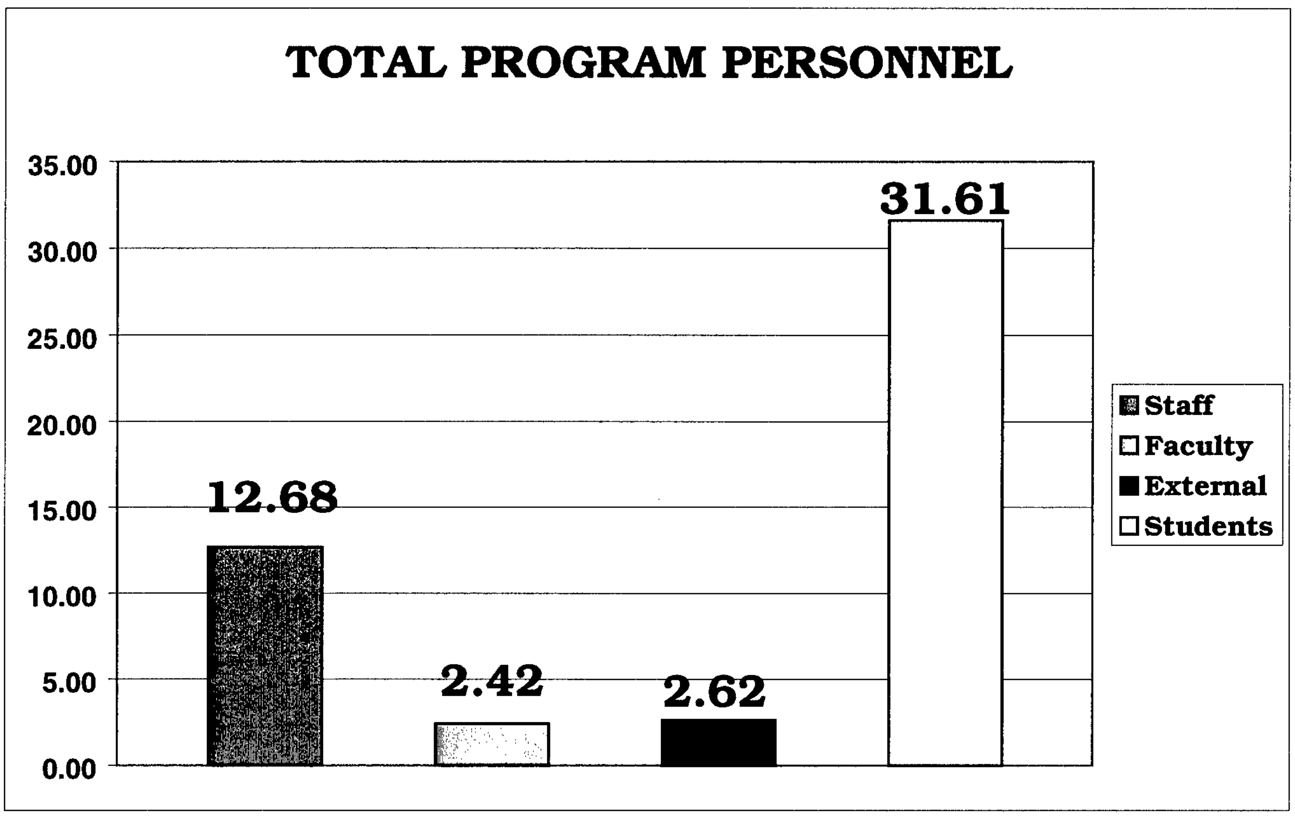


4. REFINED NPS COST MODEL, REPORT SCREEN, LABOR DOLLARS REQUIRED

Staff	$4,370,458
Faculty	$1,201,992
External	$1,263,293
Students	$1,748,482

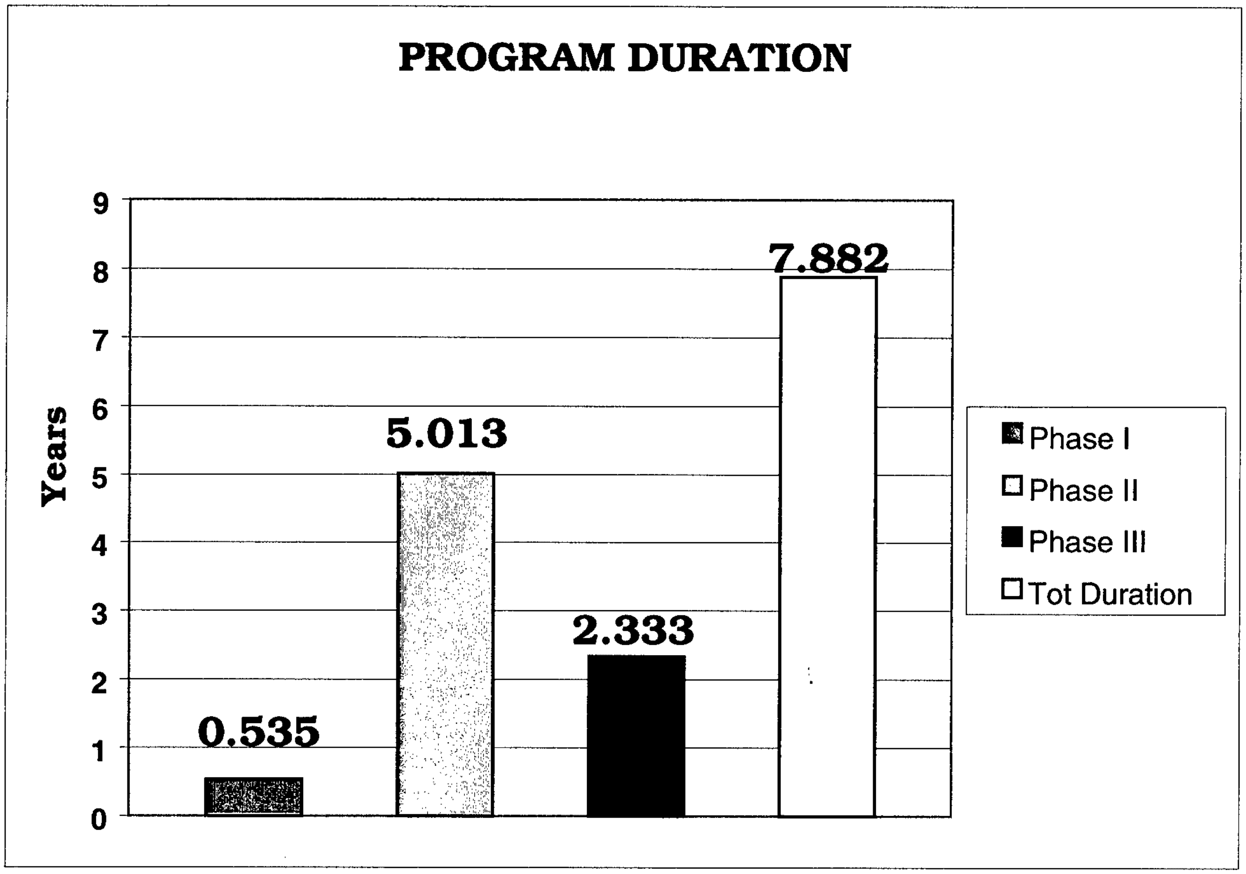


5. REFINED NPS COST MODEL, REPORT SCREEN, NUMBER OF PERSONNEL REQUIRED

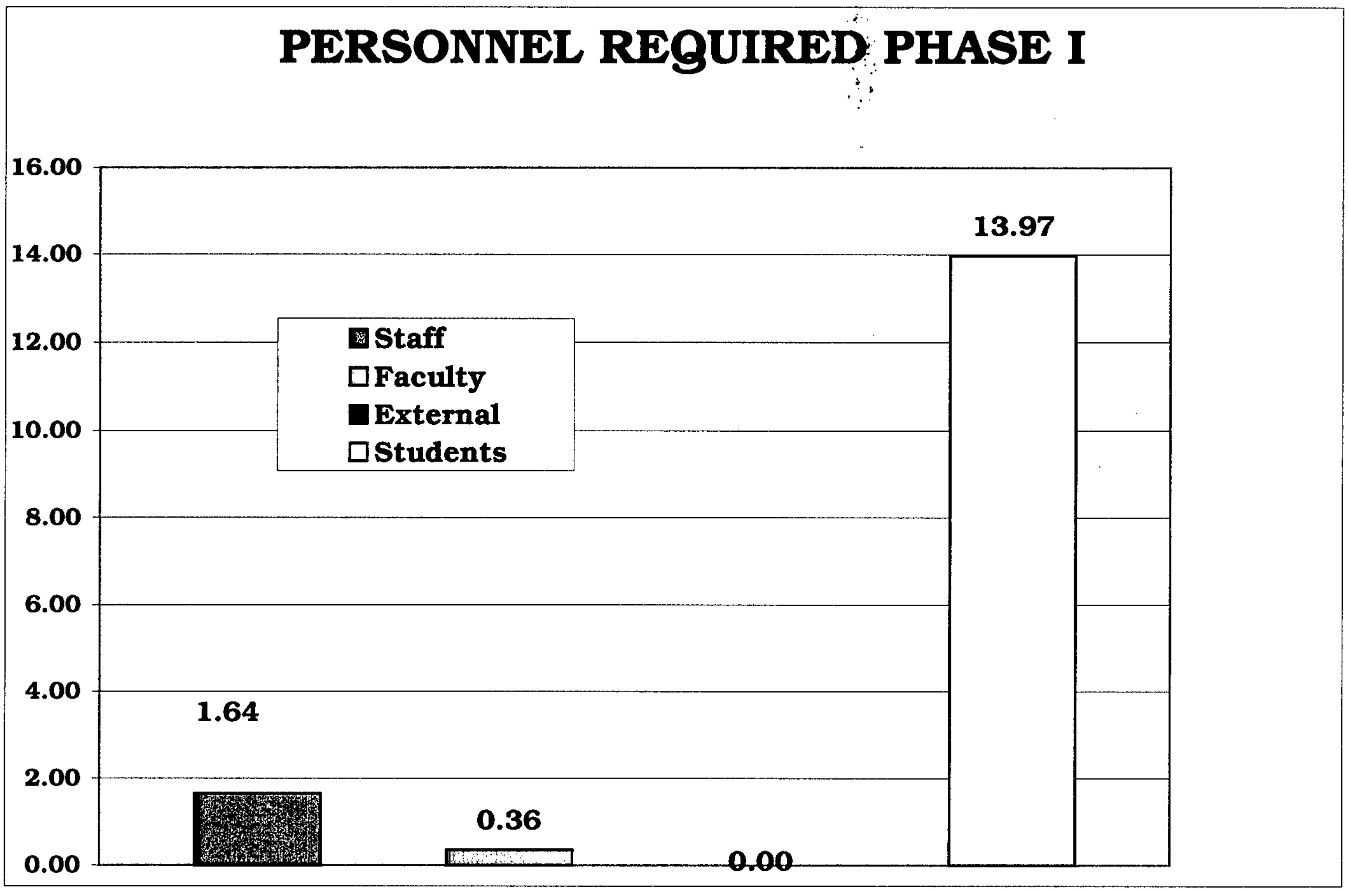


6. REFINED NPS COST MODEL, REPORT SCREEN, PROGRAM DURATION (MONTE CARLO GENERATED)

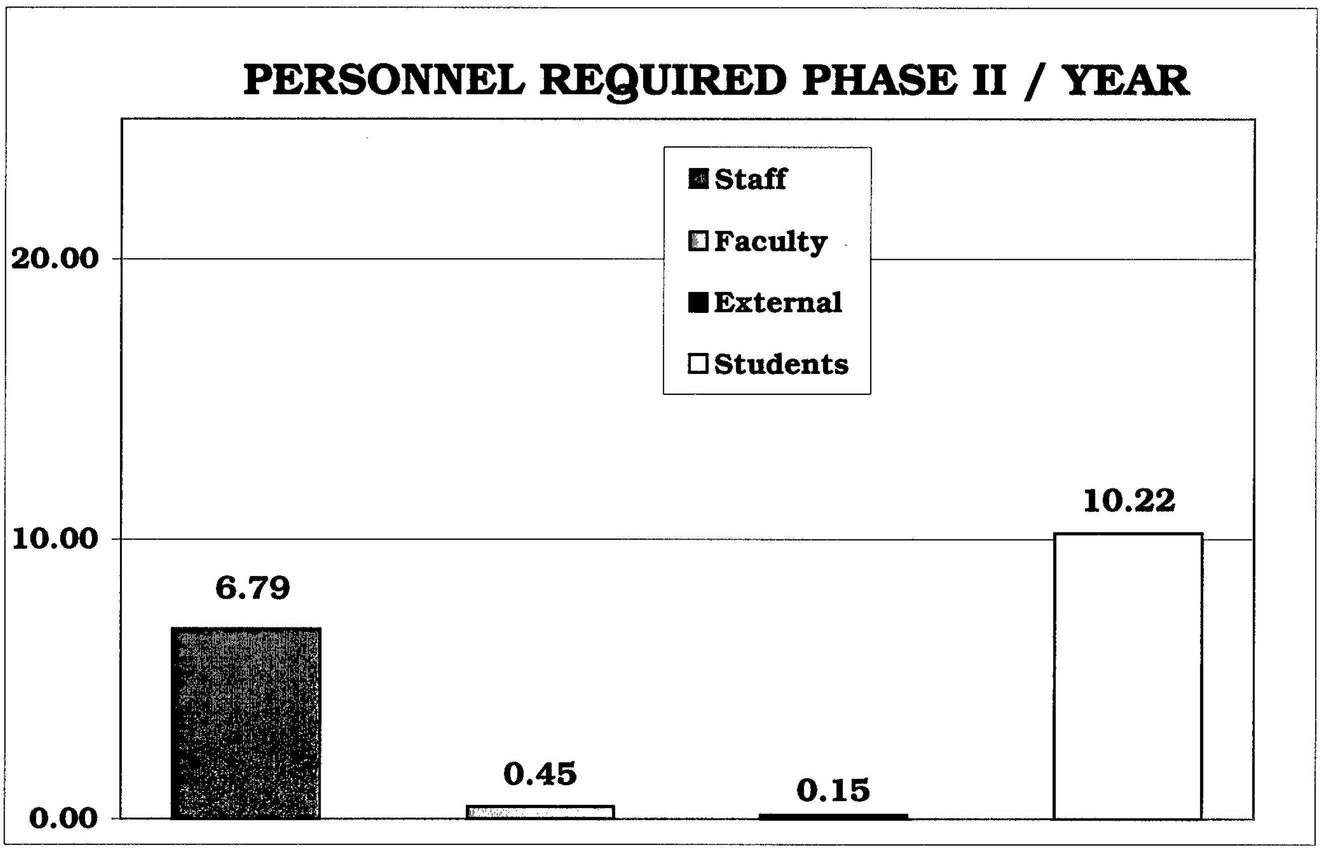
PROGRAM LENGTH	Years
Phase I	0.535
Phase II	5.013
Phase III	2.333
TOTAL PROGRAM DURATION	**7.882**



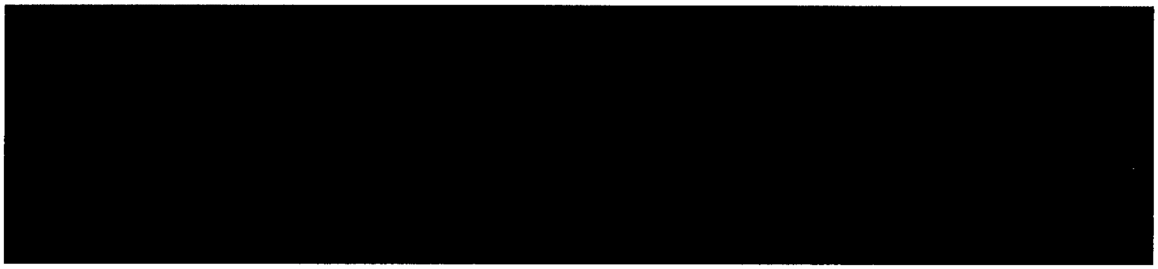
7. REFINED NPS COST MODEL, REPORT SCREEN, PERSONNEL REQUIRED BY PHASE (PHASE I)

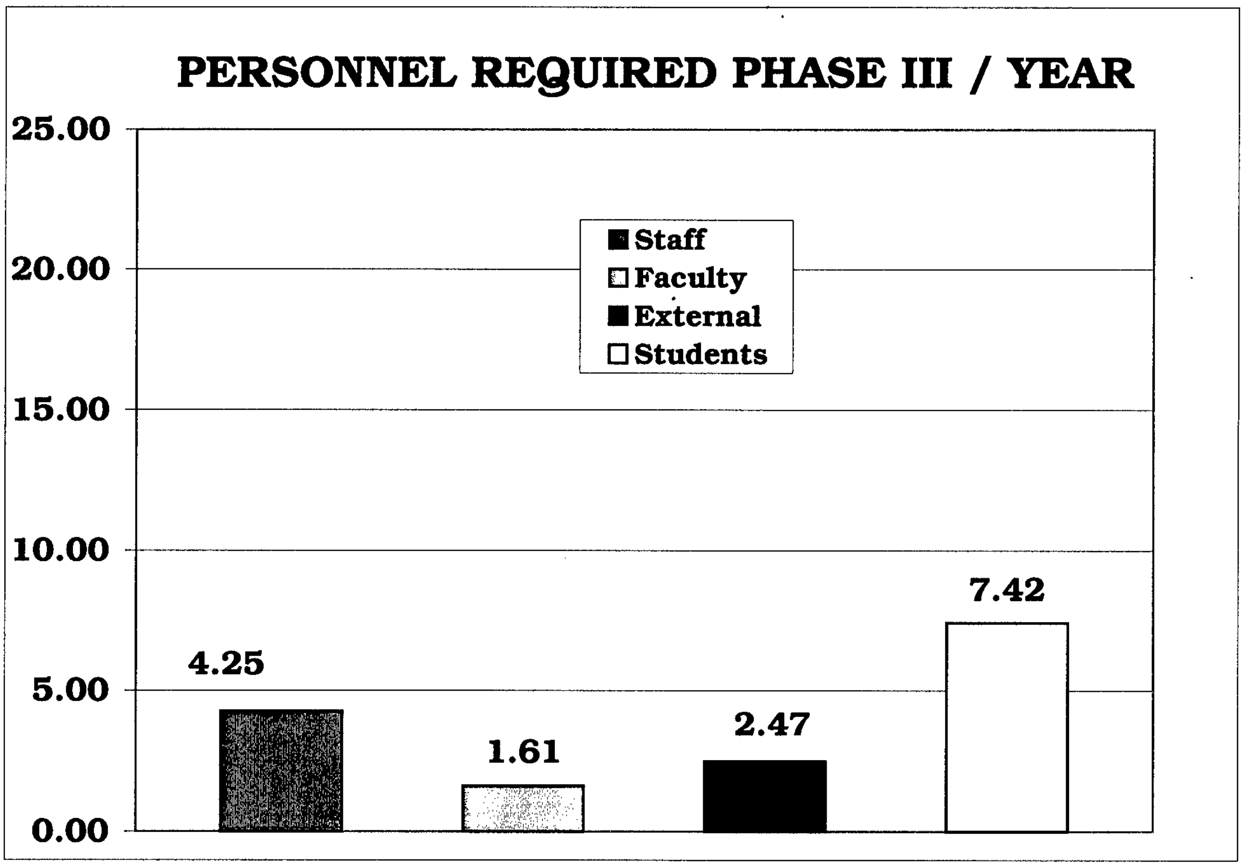


8. REFINED NPS COST MODEL, REPORT SCREEN, PERSONNEL REQUIRED BY PHASE (PHASE II)



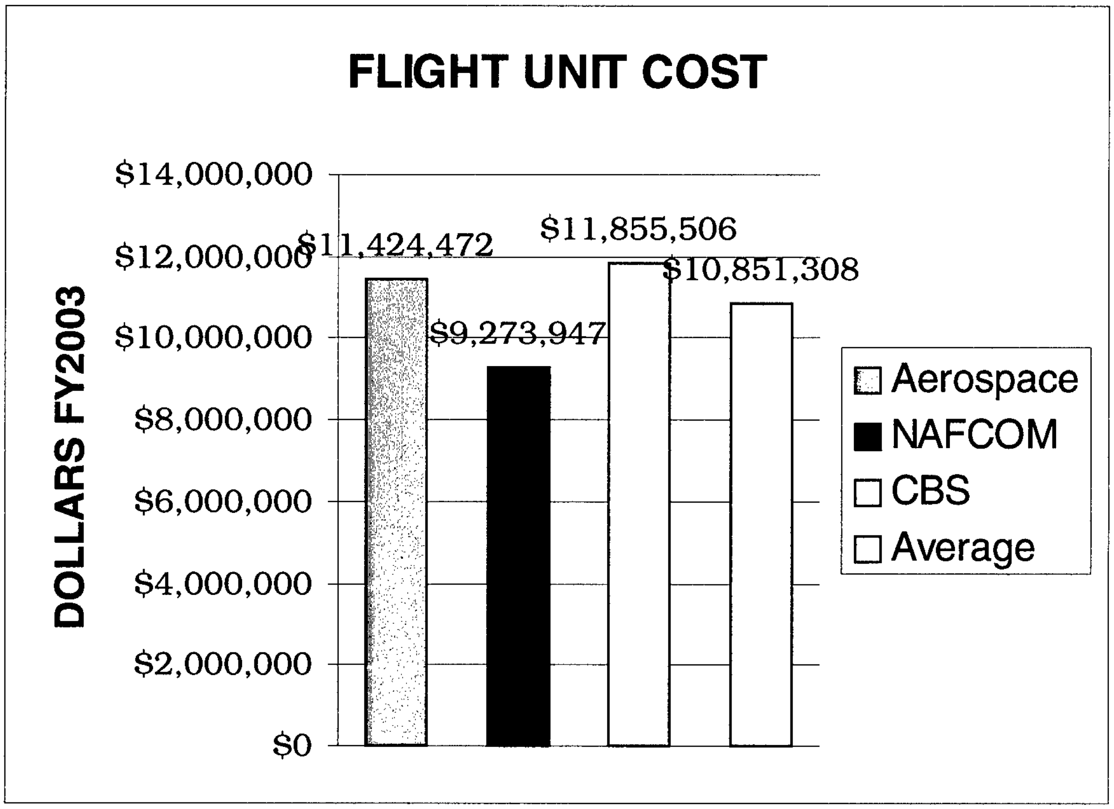
9. REFINED NPS COST MODEL, REPORT SCREEN, PERSONNEL REQUIRED BY PHASE (PHASE III)





10. REFINED NPS COST MODEL, REPORT SCREEN, FLIGHT UNIT COST

[illegible]	
AEROSPACE MODEL	$11,424,472
NAFCOM	$9,273,947
CBS	$11,855,506
AVERAGE	$10,851,308
STANDARD DEVIATION (σ)	$1,382,931



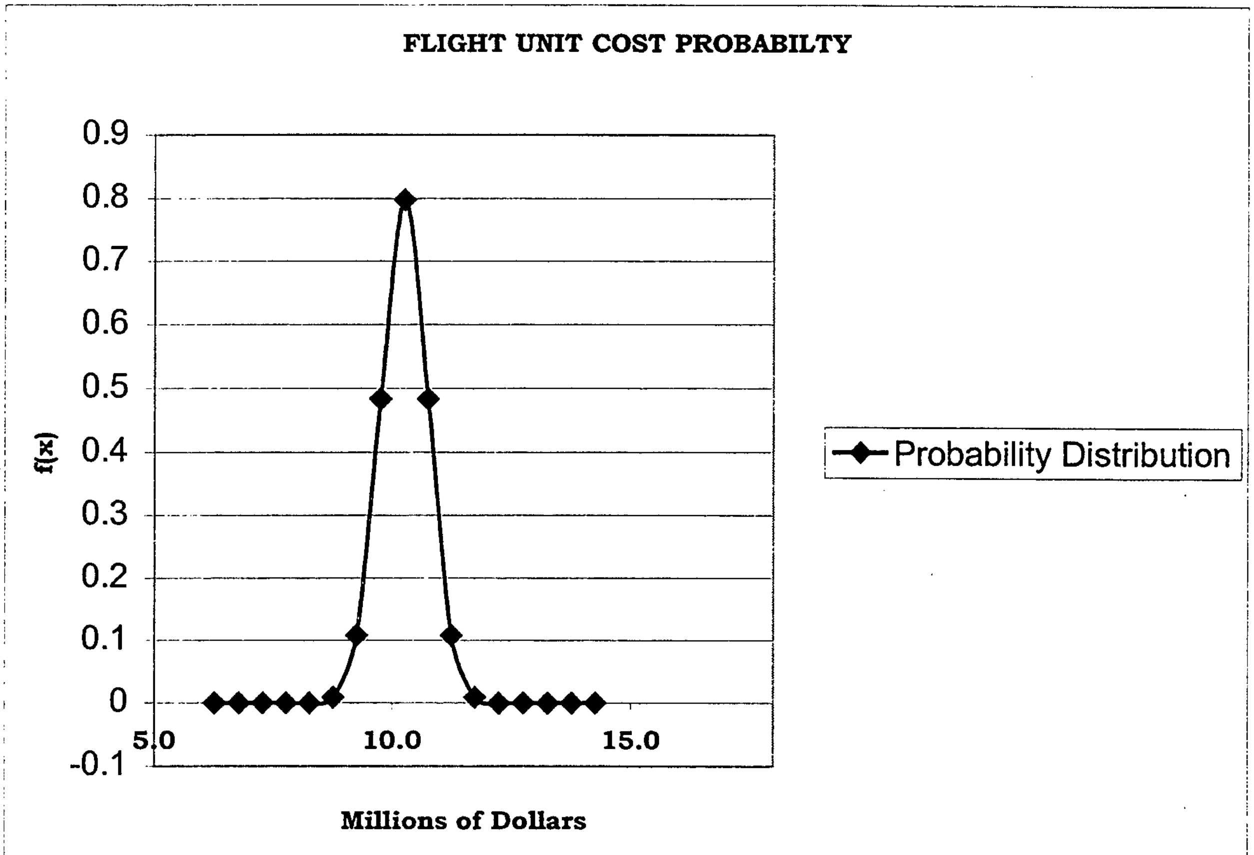
11. REFINED NPS COST MODEL, REPORT SCREENFLIGHT UNIT COST PROBABILITY DISTRIBUTION

Notes:

65% Probability Flight Unit will be within $ 9,468,377 - $ 12,234,233

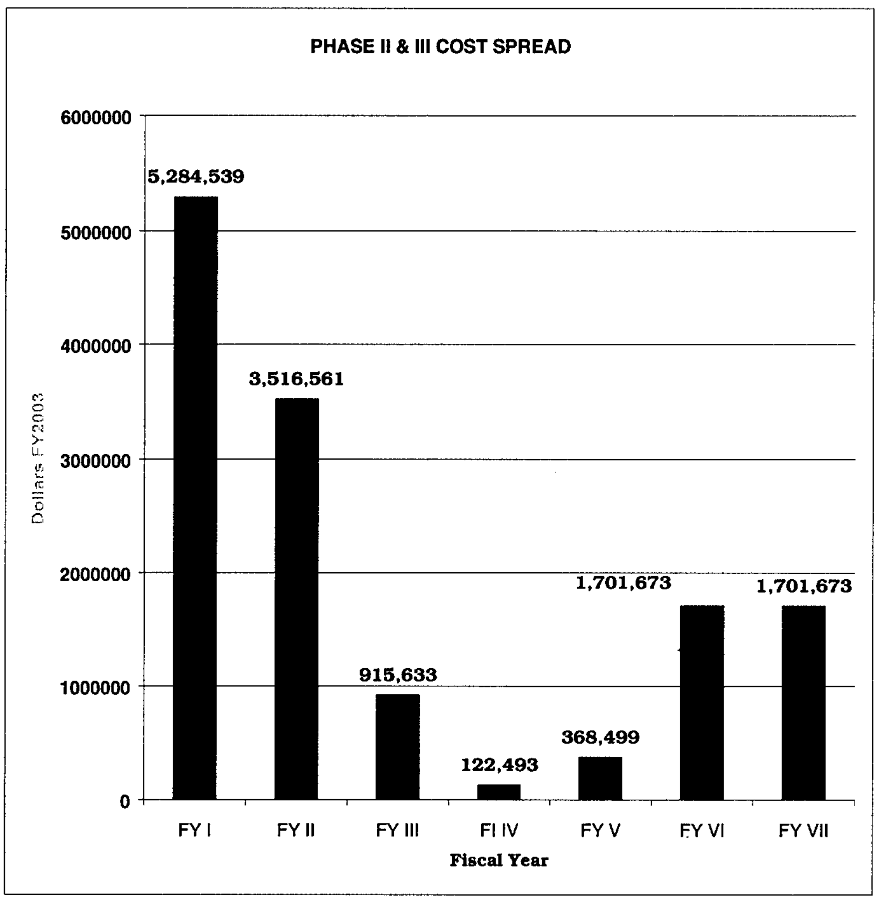
95% Probability Flight Unit will be within $ 8,085,445 - $ 13,617,171

in FY 2003$.



12. REFINED NPS COST MODEL, REPORT SCREEN, PROGRAM COST SPREAD OVER PHASE II AND PHASE III (PHASE I NOT INCLUDED)

PHASE II:	**$10,207,724**
FY I	$5,284,539
FY II	$3,516,561
FY III	$915,633
FY IV	$122,493
FY V	$368,499
TOTAL	**$10,207,724**
PHASE III	**$3,403,345**
FY I	$1,701,673
FY II	$1,701,673
TOTAL	**$3,403,345**



13. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] SCHEDULE DURATION (MONTE CARLO APPLICATION)

SCHEDULE DURATION MONTE CARLO APPLICATION		
Phase I	**Phase II**	**Phase III**
0.500	4.000	2.000
0.530	4.800	2.280
0.575	6.240	2.720
0.535	5.013	2.333
7.882		
90.00	**%This is converted to years and added to Total above.**	
8.13		

14. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] PHASE I,II, AND III LABOR HOURS (MONTE CARLO APPLICATION)

LABOR HOURS MONTE CARLO APPLICATION						
Staff Hours				**External Hours**		
Phase I	**Phase II**	**Phase III**		**Phase I**	**Phase II**	**Phase III**
1.232	40.460	13.390	Min	0	1.785	7.800
1.306	42.888	14.595	Most Likely	0	1.892	8.502
1.417	46.529	16.604	Max	0	2.053	9.672
1.319	43.292	14.863	Average	0	1.910	8.658
59.474			Total	10.56795		
Faculty Hours				**Student Hours**		
Phase I	**Phase II**	**Phase III**		**Phase I**	**Phase II**	**Phase III**
0.267	5.355	5.070	Min	3.493	13.175	7.800
0.282	5.676	5.526	Most Likely	3.703	15.020	8.502
0.306	6.158	6.287	Max	4.017	17.918	9.672
0.285	5.730	5.628	Average	3.738	15.371	8.658
11.643			Total	27.766		
Phase I	Phase II	Phase III				
5.341	**66.303**	**37.807**				

Note: The Labor hours for Phase II are not used directly. Only the ratio of personnel/total Phase II hours. For example, Staff to total ratio is 43.292/66.303 which is a ratio of 65.294%. This is multiplied by the Labor subtotal in the Phase II calculation page. From this value we can arrive at a dollar amount for Staff for Phase II. Dividing by the Staff engineer wage of $65/hr.. this yields the actual number of Phase II Staff hours expected per the Report page of the NPS COST MODEL.

15. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] PHASE I

PHASE I COMPUTATIONS

LABOR HOURS: (Thousands)		LABOR DOLLARS: (FY00$K)	
Staff	1,319	Staff	$60,659
Faculty	285	Faculty	$36,785
External	0	External	$0
Students	3,738	Students	$171,930
Total	**5,341**	**Total**	**$269,374**

OTHER (DOLLARS)			
Management	$52,637		
Overhead	$37,598	**Total Phase I $**	**$379,912**
Fees	$0		
G & A	$18,799		
Hardware/Materials	$0		
Testing	$0		
Software	$1,504		
Total Other (Dollars)	**110,538**		

LABOR (Hours) for PHASE I / Year	
Staff	2,465
Faculty	533
External	0
Student	6,986
Total	9,984
LABOR (Hours) Available for ONE person / Year	
Staff	1,500
Faculty	1,500
External	1,500
Student	500
Total	5,000
PERSONNEL REQUIRED for PHASE I	
Staff	**1.6**
Faculty	**0.4**
External	**0.0**
Student	**14.0**
TOT PERSONNEL REQUIRED FOR PHASE I	**16.0**

16. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] PHASE II

PHASE II

COST MODELS	Aerospace (NPS)	NAFCOM	CBS	Average
Model Results (FY03$)	$27,046,520	$20,510,000	$21,601,767	
Monte Carlo Confidence Rating	VH	MH	M	
Min	$27,046,520	$20,510,000	$21,601,767	
Most Likely	$28,128,381	$22,355,900	$31,538,579	
Max	$29,751,172	$25,432,400	$49,900,081	
Average	**$28,308,691**	**$22,766,100**	**$34,346,809**	**$28,473,867**

	Aerospace(NPS)	NAFCOM	CBS	Average
LABOR (DOLLARS) [PHASE II]				
Labor with Single Contractor (85%)	$24,062,387	$19,351,185	$29,194,788	
Labor for Univ. Environment (40% of 85%)	$9,624,955	$7,740,474	$11,677,915	
Reduct Factor for inhouse Test (30%)	$2,887,486	$2,322,142	$3,503,375	
Labor Subtotal	**$6,737,468**	**$5,418,332**	**$8,174,541**	**$6,776,780**
Includes Maint/Overhead/Fees/G&A				
5% Maintenance	$336,873	$270,917	$408,727	$338,839
10% Overhead	$673,747	$541,833	$817,454	$677,678
5% Fees	$336,873	$270,917	$408,727	$338,839
5% G&A	$336,873	$270,917	$408,727	$338,839
Maint/Overhead/Fees/G&A Subtotal	**$1,684,367**	**$1,354,583**	**$2,043,635**	**$1,694,195**
Pure Labor $ for Phase II	**$5,053,101**	**$4,063,749**	**$6,130,905**	**$5,082,585**
Staff	$3,299,405	$2,653,410	$4,003,153	$3,318,656
Faculty	$436,686	$351,187	$529,829	$439,234
External	$145,562	$117,062	$176,610	$146,411
Student	$1,171,449	$942,090	$1,421,314	$1,178,284

NOTES:

Staff Labor dollars are calculated by the following:

Find Labor Ratio: Staff Labor Average Hours for Phase / Labor total(Staff/Faculty/External/Student

This is found in the Calculations Section of this workbook.

This Ratio is then multiplied by the **Pure Labor $ for Phase II** above.

Similarly for Faculty, External, & Student.

Due to the duration of Phase II (Design and Development), the ratios are probably more accurate than the actual Labor Hour figures from the worksheet completed by the user in the NPSMODEL Spreadsheet.

17. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] PHASE II – PAGE 2

	Aerospace(NPS)	NAFCOM	CBS	Average
LABOR (HOURS) [PHASE II]				
Staff	50,760	40,822	61,587	51,056
Faculty	3,385	2,722	4,107	3,405
External	1,128	907	1,369	1,135
Student	25,466	20,480	30,898	25,615
Total	80,740	64,932	97,961	81,211
LABOR (Hours) for PHASE II / Year				
Staff	10,125	8,143	12,285	10,184
Faculty	675	543	819	679
External	225	181	273	226
Student	5,080	4,085	6,163	5,109
Total	16,105	12,952	19,540	16,199
LABOR (Hours) Avail for 1 person / Year				
Staff	1,500	1,500	1,500	1,500
Faculty	1,500	1,500	1,500	1,500
External	1,500	1,500	1,500	1,500
Student	500	500	500	500
Total	5,000	5,000	5,000	5,000
PERSONNEL REQ'D for PHASE II				
Staff	6.8	5.4	8.2	6.8
Faculty	0.5	0.4	0.5	0.5
External	0.2	0.1	0.2	0.2
Student	10.2	8.2	12.3	10.2
TOT PERSONNEL REQUIRED	7.4	5.9	8.9	7.4

PHASE II	**Aerospace(NPS)**	**NAFCOM**	**CBS**	**Average**
Satellite Bus Cost (Hardware/Materials)	$4,246,304	$3,414,915	$3,240,265	$3,633,828
Satellite Bus Cost (Labor)	$6,737,468	$5,418,332	$8,174,541	$6,776,780
Total Bus Cost	$10,983,772	$8,833,247	$11,414,806	$10,410,608
Payload Cost + 30% (Hardware/Materials/Labor)	$440,700	$440,700	$440,700	$440,700
Total Payload Cost	$440,700	$440,700	$440,700	$440,700
TOTAL FLIGHT UNIT COST	$11,424,472	$9,273,947	$11,855,506	$10,851,308

18. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] PHASE III

PHASE III

	Worksheet	Confidence	Monte Carlo Result
LABOR (HOURS)			
Staff	13,390.00	MH	14,863
Faculty	5,070	MH	5,628
External	7,800	MH	8,658
Student	7,800	MH	8,658
Total	**34,060**		**37,807**
LABOR (DOLLARS)			
Staff	$966,089		
Faculty	$725,973		
External	$1,116,882		
Student	$398,268		
Total	**$2,808,944**		
OTHER (DOLLARS)			
Hardware / Materials / Supplies (70%)	$81,667	L	$112,972
G&A / Fees / Maint / Travel (20%)	$23,333	M	$27,222
Overhead (10%)	$11,667	H	$12,483
Total	**$116,667**		**$140,194**

Total Labor Dollars	**$2,808,944**
Total Other Dollars	**$140,194**
TOTAL PHASE III DOLLARS	**$2,949,138**

NOTES:

Total "OTHER (DOLLARS)" is calculated by the following method:

ASSUME $50,000/year for OTHER.

Multiply by 1.13 to convert from FY99 to FY03 dollars

Result is then multiplied by Average duration for Phase III calculated in "Calculations" section of this workbook.

Hardware/Materials/Supplies is approximately 70% of OTHER DOLLARS total.

G&A/Fees/Maint/Travel is approximately 20% of OTHER DOLLARS total.

Overhead is approximately 10% of OTHER DOLLARS total.

19. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] PHASE III – PAGE 2.

LABOR (Hours) for PHASE III / Year	
Staff	6,370
Faculty	2,412
External	3,711
Student	3,711
Total	16,203
LABOR (Hours) Available for ONE person / Year	
Staff	1,500
Faculty	1,500
External	1,500
Student	500
Total	5,000
PERSONNEL REQUIRED for PHASE III	
Staff	**4.2**
Faculty	**1.6**
External	**2.5**
Student	**7.4**
TOTAL PERSONNEL REQUIRED FOR PHASE III	**15.7**

20. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] PHASE III LABOR

ALL DOLLAR FIGURES ARE FY00 PHASE III LABOR DOLLARS MONTE CARLO APPLICATION		
Staff Dollars		**External Dollars**
Phase III		**Phase III**
$966,089	Min	$1,116,882
$1,053,036	Most Likely	$1,217,401
$1,197,950	Max	$1,384,934
$1,072,358	Average	$1,239,739
Faculty Dollars		**Student Dollars**
Phase III		**Phase III**
$725,973	Min	$398,268
$791,311	Most Likely	$434,112
$900,207	Max	$493,852
$805,830	Average	$442,077
$3,560,005		

DOLLARS (MONTE CARLO APPLICATION)

21. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] PHASE III OTHER

PHASE III "OTHER DOLLARS" MONTE CARLO APPLICATION		
Hardware,Materials,Suppliess(70%)		**G&A,Fees,Maint,Travel(20%)**
$81,667	Min	$23,333
$106,167	Most Likely	$26,600
$151,083	Max	$31,733
$112,972	Average	$27,222
Overhead (10%)		
$11,667		
$12,367	**Total OTHER $**	**$140,194**
$13,417		
$12,483		

DOLLARS (MONTE CARLO APPLICATION)

22. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] GROUND SUPPORT EQUIPMENT (NOT ASSOCIATED WITH ANY PHASE)

GROUND SUPPORT EQUIPMENT [NOT ASSOCIATED WITH ANY PHASE]	
Ground Support Equipment	
TT&C / C&DH	$40,000
EPS	$8,000
ADCS	$40,000
MISC	$12,000
TOTAL	**$100,000**

Notes:
Ground Support Equipment is any equipment required to support specific hardware elements of a sub-system. ASSUME $100,000 FY03$ FOR TOTAL.

23. NPS COST MODEL CALCULATIONS [REFINED NPSAT ANALYSIS] FISCAL YEAR COST

TOTAL PROGRAM COSTS SPREADER BY FISCAL YEAR

Phase II Duration	5.013		Mult Factors
Phase II Cost	**$10,207,724**		
FY I	$5,284,539		0.5177
FY II	$3,516,561		0.3445
FY III	$915,633		0.0897
FY IV	$122,493		0.012
FY V	$368,499		0.0361
Total	**$10,207,724**		

Phase III Cost	**$3,403,345**
FY I	$1,701,673
FY II	$1,701,673
Total	**$3,403,345**

FISCAL YEAR EXPENDITURES	
FY I	$5,284,539
FY II	$3,516,561
FY III	$915,633
FI IV	$122,493
FY V	$368,499
FY VI	$1,701,673
FY VII	$1,701,673

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